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MARITIME
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LEARNING

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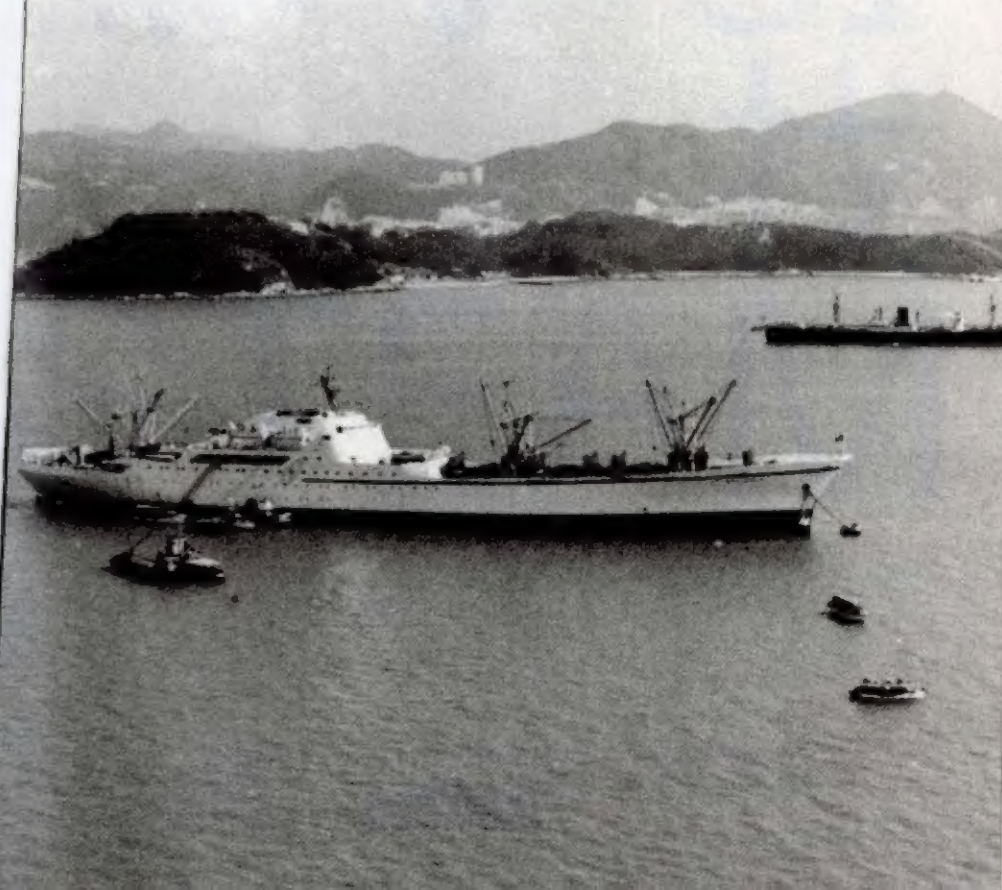
A Revolution in Maritime Trade and Warfare

海上貿易和
軍事的革命

Dr Stephen Davies
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STEAM X
MARITIME
MUSEUM
LEARNING

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DONATION

- 1 S.T.E.A.M. — Science, Technology, Engineering, Arts and Mathematics.
「S.T.E.A.M.」即科學 (Science)、科技 (Technology)、工程 (Engineering)、
藝文 (Arts)、數學 (Mathematics) 的縮寫簡稱。

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Foreword - D38
2021

The Hong Kong Maritime Museum (HKMM) is dedicated to making our audiences aware of the importance of maritime history, culture, and heritage for our daily lives in this fabulous port city. We enhance this awareness through our exhibitions and education programmes.

Led by the museum's Education Team, the *STEAM × Maritime/Museum Learning* project focused the crucial role of steam in maritime historical developments through STEAM, the acronym widely used in education today that stands for Science (S), Technology (T), Engineering (E), Arts (A) and Mathematics (M).

As part of the HK SciFest 2020 programmes, the HKMM has put together a mini exhibition, a maritime-theme public talk, an AI robot demonstration developed by students from The University of Hong Kong, and student activities. This book publication, *The STEAM of steam — A Revolution in Maritime Trade and Warfare*, is the last of the series of deliverables.

We thank our audiences for their great support on this project. Given the pandemic situation, it has been a challenge not only for us to produce an exhibition, but also for them to visit the museum. I also thank the author, Dr Stephen Davies, for sharing his knowledge with us. Furthermore, we most cordially like to thank the staff of the Swire HK Archive Service for their assistance. Last but not least, we want to express our sincere gratitude to the Maritime and Aviation Training Fund (MATF), Transport and Housing Bureau for their funding support.

Professor Joost Schokkenbroek
Museum Director
Hong Kong Maritime Museum



序言

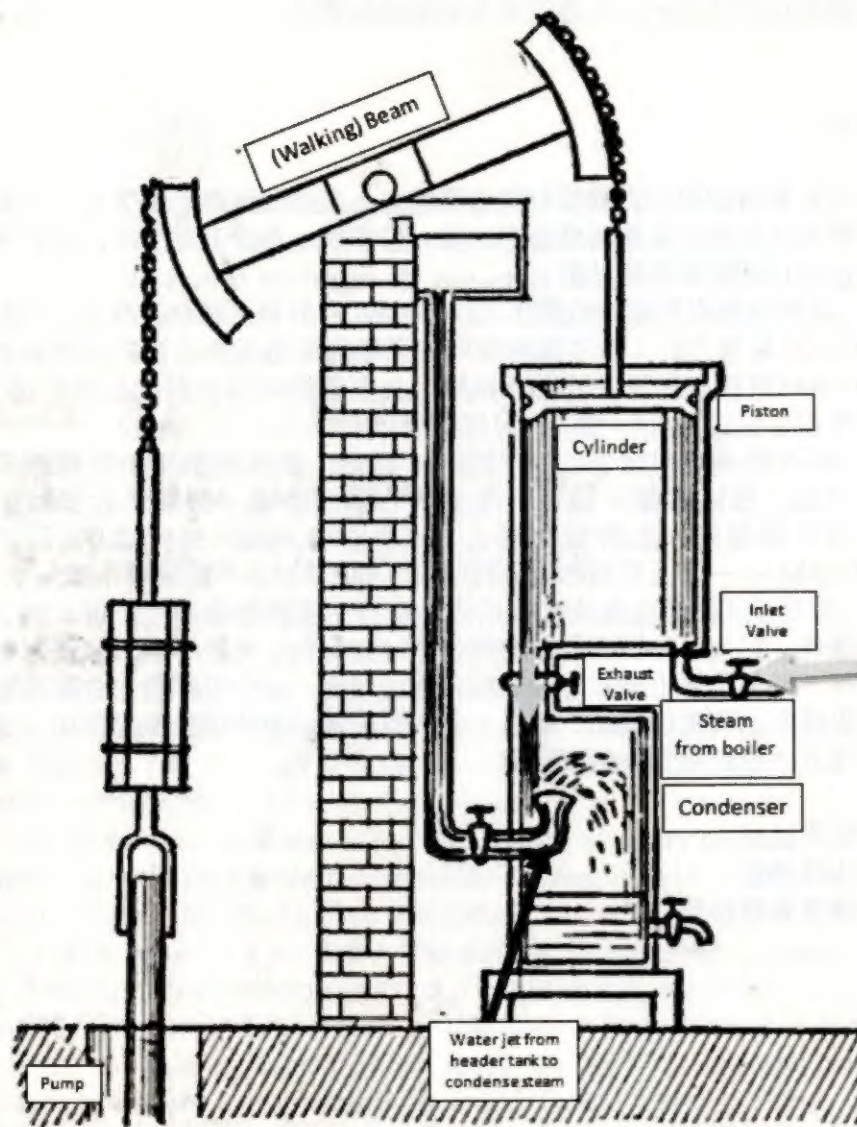
香港海事博物館致力提倡有關海事歷史、文化和遺產的重要性，及其如何影響活在如此美麗海港城市的每一位市民。為提高此意識，我們不斷推出各類展覽和教育計劃。

在博物館教育組的統籌下，「STEAM × 海事／博物館學習」計劃以STEAM教育方針，集中探討蒸汽在海事歷史發展中扮演的關鍵角色。STEAM教育方針現今被廣泛採用，各字母縮略詞分別代表科學(S)、科技(T)、工程(E)、藝文(A)和數學(M)。

作為香港科學節2020計劃的一部分，香港海事博物館籌劃了不同活動，包括微展、以海事為主題的公眾演講、由香港大學學生示範自行開發的人工智能機器人，以及學生活動。這本書《從蒸汽找STEAM——海上貿易和軍事的革命》是此活動系列中最後一環。

我們感謝觀眾對是次計劃的鼎力支持。疫情肆虐不僅影響本館之日常運作，對大眾參觀博物館來說也是一個挑戰。此外，本人感謝作者史提芬·戴偉思博士慷慨地分享他寶貴的知識；並十分感激太古集團香港歷史檔案服務提供協助。最後，我們要向贊助機構運輸及房屋局海運及空運人才培訓基金作由衷致謝。

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Parts of James Watt's first single-acting steam engine.

(Source: N.H. Black & H.N. Davis, Practical physics:
Fundamental principles and applications to daily life, New York: Macmillan, 1921.)

科學家瓦特 (James Watt) 第一台單動式蒸汽引擎的局部說明。

(資料來源：N.H. Black & H.N. Davis。

《實用物理學：基礎理論與日常生活應用》，紐約：麥克米倫，1921年。)

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蒸汽機的 科創教育世界

INTRODUCING STEAM'S S.T.E.A.M. WORLD

Marine steam engines and boilers were the principle agents, along with screw propellers and iron, then steel, hulls, of a massive maritime revolution. The story of how they developed is fascinating. Steam power is a typical example of how world-changing technical developments draw inspiration both directly and indirectly from a very wide range of human activities, of ways of thinking and of different cultures. But what you will also read in what follows is a tale of how creative thinkers and doers, although they have marvellously open minds capable of amazing lateral leaps of imagination, also have imaginations that can be constrained by the narrower horizons of the world in which they live.

船用蒸汽引擎、鍋爐，以至螺旋槳、鐵製和其後鋼製的船身，都是大規模海事革命的基本媒介。它們的發展故事相當引人入勝。改變世界的科技發展是如何從大規模而廣泛的人類活動、思考模式與不同文化直接或間接地得到靈感？蒸汽動能的發展就是個非常典型的例子。不過，接下來您將會讀到的故事中的思想家和實幹者，儘管他們有驚人的開創性思維，能觸類旁通，然而有些想像力仍會受當時視野較為狹隘的世界所約束。

We can begin by noticing that, during the first century and a half of the story of the steam engine, strictly speaking there was no S.T.E.A.M. That is, there were no people called scientists, technologists or engineers. Even artist and mathematician were little used terms, as a look at the history of the words in English shows. Instead, at the outset of the story of the steam engine, let's say in the mid-17th century, it is helpful to think of a world divided into mainly thinkers, a comparatively small circle of the privileged, who had the time and opportunity to exercise their curiosity, and discuss and experiment with their ideas — they called themselves natural philosophers — and a much larger number of mainly doers, who had to get things done in order to feed, house and clothe themselves and their families.

Within a century — so by the mid-18th century — a new category of person had emerged: a thinking doer, who was closely involved in creating the huge number of innovations without which there would never have been any steam engines at all. These were the people who, by the 19th century, had become the great drivers of the steam revolution: engineers, mechanics and draftsmen. Meanwhile in the background the more dedicated theorists — the word 'scientist' wouldn't be invented until 1833 — kept adding to the understanding of how everything worked and could be improved, but also showed what absolute limits there were to improvements (Fig. 1.1).

It was out of the complex interactions between these groups, in the particular context of early modern Europe, that the steam engine very slowly emerged. We could well say that much of the success story of steam as a source of power to drive machines like pumps, weaving machinery, hammers,

vehicles and ships was because we know that steam was a hot gas and understanding knowledge in terms of the sub-divided world of S.T.E.A.M. lay in the future.

To begin with, while the thinkers puzzled about what they called — following the person associated with the first ever steam engine (really more of a toy (Fig. 1.2)), Hero of Alexandria (c.10 CE — c.70 CE) — pneumatics, the doers could get on with solving the technical problems they had to deal with without worrying too much about why the machines they invented actually worked.

In the late 16th century, the thinkers began puzzling about a very old problem. We needn't worry about the detail, but traditionally in the Western world it had been held that a vacuum couldn't exist. Then, around the beginning of the 17th century in Europe, experiments began looking at what we call air pressure: what made it what we experience on the surface of the Earth and how and why it varied. The science that would eventually explain steam engines had begun before there were either science or steam engines.

Meanwhile the doers, people like blacksmiths (who worked in metal), carpenters (who worked in wood), masons (who worked in stone) and a comparatively new sort of person, the mechanic (who worked with machines), were called in to help deal with a new problem. The first stirrings of what has come rather misleadingly to be called the Industrial Revolution had created a significant new technical challenge. That came about because a key material for many of the new changes was coal, which was replacing wood as the essential fuel for everything from forges to domestic fires.

To keep up with rising demand, more coal was needed and that meant mines

had to be deeper. The problem was, a lot of water leaked into the galleries of deeper mines. It needed to be pumped out. But as the mines got deeper, the horse- and water-powered pumps of the 17th century had difficulty coping. Solving that problem involved improved pump technology, which we can ignore and, which is where steam comes in, something more powerful than a horse to pump out lots of water and to keep going 24/7. The outcome, using the newly understood power of a vacuum created by condensing steam, proved to be the father of all subsequent steam engines. And from that point onward, successive designs between Edward Somerset's first attempts in 1663 and Matthew Boulton and James Watt's successful commercial engine of 1776 turned a very inefficient but reliable atmospheric engine into the classic steam engine. With Boulton and Watt, engines had become just about small enough to be used in a ship.

These improvements were almost all a product of what today we should call technology, engineering and design, in which science and mathematics played an important but often invisible part. But, with steam power rapidly developing, ever better science began providing explanations for how everything worked. The century that followed steam first driving ships and railway engines saw the greatest revolution in sea and land transport the world had ever known.

At sea, thanks to the steam engine, faster, larger, safer, increasingly more specialist ships greatly reduced the costs of carriage, both for people and goods. A useful illustration of that is the time it took people to get from Europe to Australia. In 1850 the average voyage, almost always in sailing ships, took around 90 days (or three months). Fifty years later, thanks to the steam engine,

that time had almost halved, and by 1950 it was down to less than one month.

The revolution steam engines brought to how ships were powered also helped to massively increase the volume of trade, and transform connectivity between economies and cultures. Between 1850 and 1950, world trade increased by about 1,400%, or an average of around 3% a year (Fig. 1.3). Over the same period, the number of steam-powered, ocean-going ships increased from 1,187 to 26,513 vessels in 1920, declining by 1950 to 19,254 vessels, and more or less disappearing by 1990 as the diesel engine took over. In tonnage terms, the world's steam-powered fleet over the same 100 years from went from 168,474 gross tons to over 63,542,882 gross tons — nearly 400 times the cargo volume that (Fig. 1.4), with increased ship speeds and hence numbers of voyages a year, represented an even greater increase in the volume of trade. At the same time, the average size of a steamship grew from just 142 gross tons — about half the size of a Star Ferry — to 3,300 gross tons, or 20 times the size.²

The invention — better to call it the discovery of the potential of — steam power was, like all great inventions and discoveries, the outcome of the interaction of what today we think of as S.T.E.A.M.: the five great streams of human thought. It was also the work and ideas of countless people, not just the great names mentioned in books and above all, as we shall see, not just concerned with the steam engine. As Sir Isaac Newton said, echoing a thought that can be traced back to the 12th century CE, "If I have seen further, it is by standing on the shoulders of Giants."³

There is no one moment when we can say that the steam engine was first invented. The wonderful and complex machinery powering ships great and

small that, in the decades from 1850 until the mid-20th century, linked the world more extensively and closely than ever before, emerged slowly. It was the outcome of innumerable interactions between people we now label scientists, technologists, engineers, designers and mathematicians as well as bureaucrats, businessmen and bankers over the whole realm of human productive activity as they sought, indirectly and directly, for lots of different reasons and motives, to improve the mechanical work that drove ships. Or, as economists put it today, to improve the productivity of maritime capital and labour.⁴

Much of the time everyone worked fairly independently, often only indirectly connected to others, but often linked by competitive rivalry. However, another feature of the new world that was being built, thanks to the rise of the modern printing industry and, if more slowly, fewer and fewer barriers to the exchange of ideas, was that new machinery and new ideas spread rapidly and, in spreading, fed back into even newer ideas and improved machines.

But before going on to the complicated story of the emergence of the steam engine and its application to moving ships through the water, we should briefly mention an important point about steam and the world of transport, sea transport included.

- 2 What is called a 'measurement ton' in the shipping world is a unit of VOLUME equal to 100 cubic feet (2.832 cubic metres).
- 3 Letter from Sir Isaac Newton to Robert Hooke, 5th February 1675, Box 12/11, Folder 27, Simon Gratz autograph collection, Historical Society of Pennsylvania online at <https://digitallibrary.hsp.org/index.php/Detail/objects/9792>.
- 4 Productivity is defined as the ratio between units of output and units of input in terms of quantity, quality and cost.

故事開始於一個「科學家」、「工程師」、「技工」等概念都未出現的年代，甚至連「藝術家」和「數學家」等字眼也鮮有出現的英語世界，在這環境中，科創教育(S.T.E.A.M.)的觀念並不存在。蒸汽引擎故事的開端在17世紀中葉，想像人們主要分為思想家——一群相對小撮的特權階級(他們有時間和機會去探索他們感好奇的事物，甚至可以進行討論和實驗，他們叫自己做「自然哲學家」)，和其餘佔較多數為口奔馳的工匠／工作的人。

接著不到一個世紀，即大約在18世紀中葉，一個嶄新的分類出現——「思考的實幹者」(thinking-doer)，他們共同創造了許多新發明，若沒有這些發明，蒸汽引擎根本不會出現。到了19世紀，這群人——工程師、技術人員、繪圖師，成為蒸汽革命的重要推動者。與此同時，更專門的理論家(「科學家」是在1833年才出現的新詞語)不斷令人們理解事物如何運作、如何改良，但同時展示了改良過程中所面對的限制(圖1.1)。

正因為這些界別之間在歐洲早期的複雜互動，蒸汽機才能制成面世。可以說，很多以蒸氣驅動的機械，如泵、編織機器、錘子、車輛或船等得以成功開發，都是基於對蒸汽(熱氣)的認知，以及後來從其他科創教育(S.T.E.A.M.)範疇中獲得到新的知識。

首先，當思想家對最早的蒸汽機(其實更像一個玩具(圖1.2))和希羅(Hero of Alexandria, 公元10-70年)的《氣體力學》感到疑惑時，實幹者們只是一心解決工作上必須處理的技術問題，毋須探討他們發明的機械的運作原理。

16世紀後期，「思想家」開始為一個古老的問題而煩惱。我們毋須理會細節，但傳統西方世界一直堅持真空是不可能存在。到17世紀初的歐洲，實驗開始留意到我們後來稱為氣壓的東西，它究竟是怎樣形成？我們在地球表面體驗著甚麼？它為何且如何變化？早在「科學」的概念和蒸汽機出現之前，能解釋蒸汽機原理的科學其實已一直在運作。

與此同時，實幹者們——鐵匠、木匠、石匠，以至新興的機械技工等，亦要協助處理一個新的問題。「工業革命」(一個誤導的命名)的苗頭帶來了重大的新技術考驗：就是煤的出現，這東西取代了木材成為家居或燭鐵的主要燃料。

為應付越來越多的需求，煤的使用量不斷增加，意味著煤礦被越採越深。問題便出現了，較深的煤礦會有大量水滲入煤坑，需要用泵把水泵出來。而在17世紀，煤礦越挖越深，當時用馬力或水力推動的泵開始應付不了。解決這個問題的方法包括改良水泵的技術——這就是蒸汽機出現的契機——人們需要比馬更有力量，可以泵走很多水，並維持無間斷運作的東西。結果，人們運用最新學習使用由冷凝蒸汽所產生真空的力量發明，最終成為隨後所有種類蒸汽引擎的「祖先」。

由那時起出現的成功設計，包括1663年薩默塞特(Edward Somerset)的初次嘗試，到1776年博爾頓(Matthew Boulton)與瓦特(James Watt)的商用發動機，把低效但可靠的「大氣引擎」變成經典的蒸汽引擎。當時博爾頓瓦特蒸汽機引擎的體積已變得細小並可以船上應用。

這種進步，是如今被我們稱為科技、工程和設計的產物，當中科學與數學扮演著極為重要卻往往不被看見的角色。不過，隨著蒸汽動能的急速發展，更精進的科學為一切運作原理提供解釋。蒸汽機引擎首次驅動船隻以及鐵路之後的那個世紀，見證著歷史上最偉大的海陸交通革命。

航海方面，藉著蒸汽引擎，更快、更大、更安全、越來越專業的船隻，大大降低了海上運輸的成本——無論是運載人還是貨物。用個較易理解的說法，就是船隻載人由歐洲到澳洲的時間：在1850年，平均航行時間約為90日(或3個月)，當中絕大多數時間是由帆推動船隻。50年後，靠著蒸汽引擎，日程幾乎減半，到了1950年，所需時間更減少至不到1個月。

蒸汽機帶來的革新，不只是推動船隻

那麼簡單，還大規模提升了貿易率，並改變了經濟和文化交流的形態。在大約1850年至1950年之間，世界貿易率飆升14倍，平均每年增長約3%（圖1.3）。期間，使用蒸汽驅動的航海船舶自1920年由1,187艘增至26,513艘，到1950年回落到19,254艘，直至1990年因被柴油引擎取代而基本上完全消失。若以噸位計算，在上述的100年裡，隨著船速和每年航行量的增加，全球蒸汽動力船隊由168,474總噸增長了近乎400倍至63,542,882總噸（圖1.4），意味著貿易率更大規模的增長。同時，蒸汽船的平均體積亦持續增大，由142總噸（即大約半艘天星小輪的大小）增長20倍至3,300總噸。²

蒸汽動能的發明（說發現其潛能較為準確），就如其他偉大發明或發現一樣，是今天被我們稱為S.T.E.A.M.（人類思想的五大分支）的互動成果。它同時是無數前人的理念和努力，而非少數書本上提及的偉人，亦不只是關於蒸汽引擎。就如牛頓引用可追溯至12世紀的諺語指：「如果我望得更遠，只因我站在巨人的肩上。」³

其實沒有所謂發明蒸汽機的一個明確時刻。這種可以驅動著大小船隻、自1850年至20世紀中將世界連繫起來的奇妙而複雜的機械，是逐步研發出來的。驅動著這類研究和改良工作是科學家、技工、工程師、設計師、數學家，還有官僚、商人、銀行家等界別，各抱著不同原因與動機去改善驅動船舶的機械工作，其中包括為增進海事資本和勞動力的生產率⁴。蒸汽機就是這些不同界別的精英直接或間接交流的結果。

大部分時間他們都是各自工作，他們的工作通常僅與其他人的工作間接地連繫，而這種連繫往往是出於競爭。可是，為建立這個嶄新的世界，還要感謝現代印刷工業，使思想交流的障礙持續減少，令新機械和新思想迅速傳播，不斷促進新的思想和機械的改良。

在講述複雜的蒸汽機開發故事之前，我們需要稍稍回顧有關蒸汽以及全球交通（包括海上交通）很重要的一點。

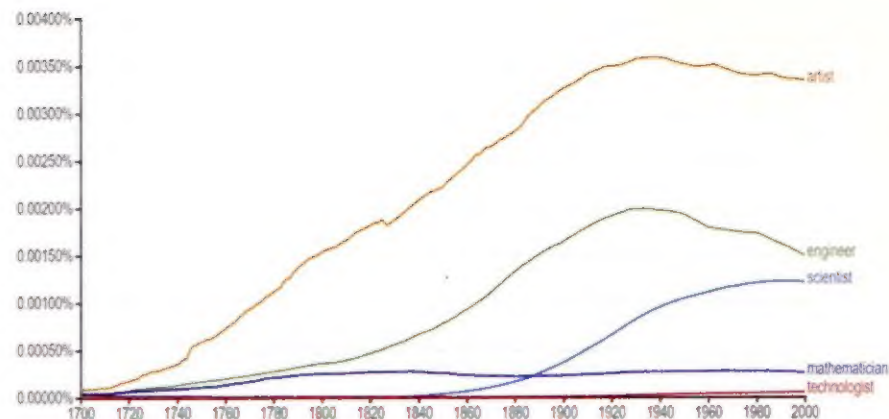


Figure 1.1: The emergence and growing use of the words 'scientist', 'technologist', 'engineer', 'artist' and 'mathematician' in English, 1700-2000.
(Source: Google Ngram.)

圖1.1：1700至2000年間，「科學家」、「技師」、「工程師」、「藝術家」、「數學家」等詞在英語世界中的出現與使用率的增長。
(資料來源：Google Ngram。)



Figure 1.2: Hero of Alexandria's 'aeropile', which was driven by steam, but not as steam engines would be.
(Source: Wikipedia.)

圖1.2：希羅的「汽轉球」由蒸汽推動，但並不像後來的蒸汽引擎。
(資料來源：維基百科。)

- 2 在航運世界中，所謂的「呎碼噸」是指等於100立方英尺（2.832立方米的體積單位）。
- 3 資料來源：牛頓寫給胡克(Robert Hooke)的信。(1675年2月5日，Box 12/11, Folder 27, Simon Gratz簽名收藏，賓夕法尼亞州歷史學會，網址：<https://digitallibrary.hsp.org/index.php/Detail/objects/9792/>。)
- 4 生產率的定義是，所投入的數量、質量和成本，與產出物之間的比率。

The Rise and Decline of the Steamship

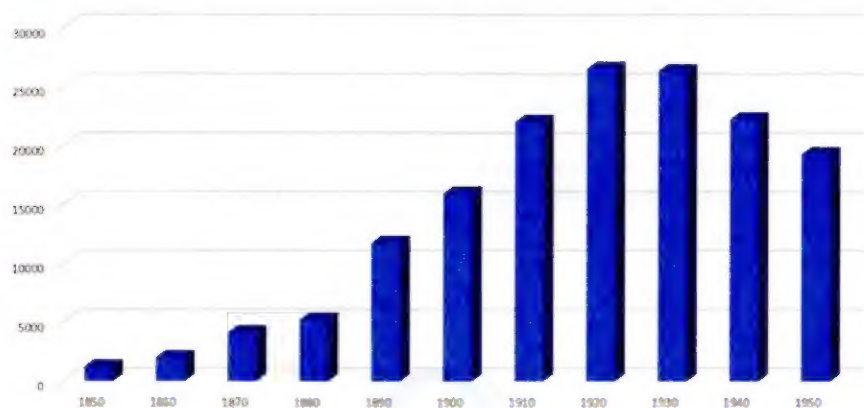


Figure 1.3: In 70 years the world's steam fleet grew 2,234%, before beginning 40 years of rapid decline.
(Source: SNGD.)

圖1.3：圖中顯示首70年全球蒸汽船隊增長了22.34倍，其後卻開始了40年的快速下降。
(資料來源：SNGD。)

The Growth in Gross Tonnage of the World's Steamship Fleet

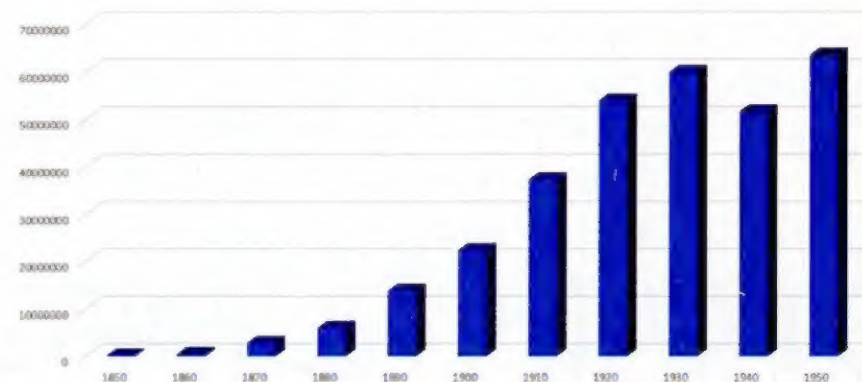


Figure 1.4: In the same century the total of steamships throughout the world grew 37,700% in gross tonnage — the uptick in 1950 reflects the arrival of the first large steam-turbine powered oil tankers.
(Source: SNGD.)

圖1.4：在全球蒸汽船總噸位飆升377倍的同一個世紀裡，於1950年的小幅度上揚顯示了首批大型由蒸汽渦輪驅動的運油船的到來。
(資料來源：SNGD。)

2

水車與船舶、 蒸汽、泵

STEAM, PUMPS, WATERWHEELS AND SHIPS

In the story of steam power, shipping is actually a latecomer. The first inefficient machine that used steam was invented by Edward Somerset in 1663, and there was an improved version by Thomas Savery in 1698. The first reliable engine, designed by Thomas Newcomen, went into service in Britain in 1712. All these early designs were intended to drive more powerful pumps to help keep mines dry. For good reasons, pumping remained steam's main use for the next 60 years. Only nearly a century later, in 1802, did William Symington install a steam engine in the small canal boat *Charlotte Dundas* to create the first reliable, steam-powered working vessel.⁵

在蒸汽動能的故事裡，船是後來才登場的。第一台以蒸汽推動的低效機器，是1663年由薩默塞特(Edward Somerset)發明的。沙維利(Thomas Savery)1698年製作了其改良版。第一台穩定地運作的引擎是由紐科門(Thomas Newcomen)設計並於1712年在英國投入服務。所有這些早期產品，都是為了推動強力水泵以保持煤礦洞乾爽。在接下來的60年，泵水仍是蒸汽機的主要使命。直至接近一個世紀之後的1802年，希明頓(William Symington)在小型運河船夏洛特·登打士號(*Charlotte Dundas*)上安裝了蒸汽引擎，才創造了第一艘可靠的蒸汽動能船。⁵

In the meantime, a point that is often overlooked, the real driver of what is called the Industrial Revolution was water power and, to a lesser extent, wind power. While the steam engine was being developed, water power from mills was powering more and more of the new factories, mines and processes. It would not be until towards the end of the 19th century that the steam engine had improved enough to be economically competitive with the best waterwheels of the day (Fig. 2.1), including hugely improved water turbines. That steam eventually replaced water and other power sources owing much to the fact that water power was not available to propel ships! But water power was harnessed to drive machines by the same technology that was used by steam engines: the paddle and the crank — two sources of feedback and development.

Technically, Thomas Newcomen's game-changing engine of 1712 was not a steam engine but, as Newcomen was careful to label it, an 'atmospheric engine' that worked by condensing a cylinder full of steam and letting atmospheric pressure push the piston down, and then, at the bottom of the stroke, letting a heavy counterweight on the other end of the horizontal beam you can see in Figure 2.2 pull the piston back up with a new supply of steam behind it.

Applying this to working a pump — the first use of steam engines — was obvious since what are called simple pumps had always sucked water up a vertical tube. So, what we see in Figure 2.2 is something we continue to see in the world of marine steam engines until the end of the 19th century. It is the beam that transferred the power of the moving piston. Newcomen had used the obvious way, like a see-saw, to get the up-and-down motion provided by his engine's

piston on one side (technically called reciprocating motion) to create an equal up-and-down motion on the other side. In marine steam engines it was called a walking beam, which propelled a crank that drove the paddles. We can see it clearly in a drawing William Symington made for one of various power transmission arrangements he submitted in a patent application in around 1801 (Fig. 2.3). It could still be seen in ferries between Hong Kong, Guangzhou and Macau as late as the 1880s (Fig. 2.4).

Something else we see in almost all early attempts at propelling boats by steam engines is the solution to turning the reciprocating motion of a piston into a rotating means of propulsion for a boat. It used two very old bits of technology: the crank and the flywheel — the second initially in the form of the paddlewheel, another very old invention (Fig. 2.5). That in itself is a perfect illustration of how technical change often uses old ideas in new applications, something that we see again and again in the story of marine steam power.

We can't point directly to anyone saying "Wah! Why don't I get the paddle to move the water rather than the water move the paddle?" But anyone who saw water propelling a wheel — an idea perhaps 6,000 years old — could easily imagine it working the other way round too.

All the early examples of water-wheels seem to have been horizontal. The first examples of a vertical wheel — which is what we see in the first steamships — are recorded in Rome in 14CE and in China at around the same time. It is also at that time that a vertical paddlewheel for propelling a vessel is first recorded both in Han Dynasty China — though it seems possible that no actual examples may have been built until the Song Dynasty — and in Rome.⁶

The Chinese design had a much simpler mechanism. It was a form of crank worked by the paddlers' feet.

The crank is a very ancient idea. It is recorded in the Mediterranean region in the 7th century BCE and, though almost certainly discovered earlier, in Han Dynasty China some 200–300 years later. As you can see clearly in Figures 2.6 and 2.7 and by inference in Figure 2.5, the crank helps turn the reciprocating motion of arms or legs into rotary motion or, working the other way, turns rotary motion into reciprocating motion (Fig. 2.6). Multiple applications of the crank were common by the time the first steam-engines appear. In one German 16th century handbook, 45 different ways of using cranks in machinery are shown.⁷ You can probably think of lots yourself.

The flywheel, or something that does the same job, was a way of dealing with the loss of power during the stroke of the reciprocating driving arm just before pull turns to push. Anyone who has ridden a bicycle knows what that feels like when their foot is at the bottom or top of the movement of pedalling and neither pulling nor pushing. The momentum — the stored energy — of the flywheel smooths out the jerky movement of the reciprocating arm providing, in theory, a steady drive. That idea is implicit in Han Dynasty China in a fan to winnow — blow the chaff of the husks away from — rice (Fig. 2.7).

The problem when it came to the steam engine was that all the early work with Newcomen design steam engines as applied to driving boats was doomed to at best only very small success, and more likely expensive failure. That's because the engines were massive, inefficient and not in fact very powerful except when compared to the horses or humans they replaced.

Significant technical and engineering breakthroughs were needed,

which was why nearly a century passed between 1712 and the 1802 success of the *Charlotte Dundas*. And then it was another 16 years before the first steam-powered ship, the *Savannah*, crossed an ocean (Fig. 2.8). From the point of view of steam power at sea, however, the *Savannah* was a failure because steam engines were still too inefficient to earn their keep. The *Savannah's* 29-day 11-hour voyage from Savannah, Georgia, USA, to Liverpool, England, in 1819 was slower than the fastest crossing made entirely under sail. The engine was only used for 80 hours. Even then, the ship ran out of fuel two days before the end of the voyage.

It would be the same story 11 years later, in 1830, when the junk-rigged steam tug *Forbes* set out from Kolkata in India to tow the Jardine Matheson opium clipper *Jamesina* to Guangzhou and became the first steamship to enter Chinese waters (Fig. 2.9). Although the *Jamesina* carried extra coal, when the ships refuelled in Singapore, 450 nautical miles (850km) from the Pearl River, the *Forbes* was in danger of running out of fuel and had to leave the *Jamesina* behind. What happened next shows the problems of early steam engines at sea. The *Forbes* took another week to make the rest of the voyage, a good part of it under sail alone. Equally, under sail alone the *Jamesina* only took two days longer. The whole voyage from Kolkata had taken 38 days, the same time it would take the record-breaking opium clipper *Red Rover* under sail alone only a year later in 1831.

The first successful entirely steam-powered ocean crossings did not come about until 1838, when they were made by the competing British ships the SS *Great Western* (Fig. 2.10) and SS *Sirius*. Even that was only a hint of what would come, for it would not be for another

30 years that the steamship began to overtake the sailing ship as a proportion of the world's shipping fleet.

It was a slow conquest. In terms of the amount of cargo carried every year, the crossover point when steam overtook sail came in the late 1870s, because steamships made quicker, more frequent voyages. The gross tonnage (i.e. internal volume) of all the world's steamships overtook sail in the early 1890s, but in terms of actual ship numbers, sailing ships still outnumbered steamships until as late as 1910. The success of maritime steam power was a long, slow story of development and change that took most of a century.

The idea of a steam-powered boat seems first to have appeared in Britain in 1729, with a design by a doctor called John Allen. Nothing seems to have been built, and how it was to be propelled appears not to be known.

Then, in 1736, Jonathan Hulls gained a patent for a paddle tug he had designed. Whether it was ever built is disputed, though one story that it was also said that it was a failure.

The first known actual working steam-powered boat appeared in the late 1770s. In France, Claude-François-Dorothée, marquis de Jouffroy d'Abbans, launched his first vessel, the *Palmipède*, in 1776. It soon sank. The successful *Pyroscaphe* took to the water seven years later (Fig. 2.7). Both were powered, as were the designs of Jonathan Hulls, by a steam engine driving a rotating paddlewheel, which was almost certainly inspired by the waterwheels that powered so much early industrial machinery.

Because of his rivalry with a more influential but less able pioneer of steam in France, and France's political situation and social system, Jouffroy never had the influence on the development of

marine steam that he should have had as society, economy and the wider cultural context played a key role in its successes and failures.

5 Although Symington had successfully trialled his first steam-powered boat in 1788, the French Marquis de Jouffroy had made a successful steam-powered boat in 1783 and, in 1787, American John Fitch had invented a very inefficient steam-powered rowing boat, the *Perseverance*.

6 By Vitruvius, whose described paddles worked by a geared capstan driven by oxen!

7 G.A. Boeckler, *Theatrum machinerum novum*, Cologne, 1662.

然而同時經常被忽視的一點是，持續了一個世紀甚至更長時間的工業革命，其真正推動力並非蒸汽，而是水力發電，風力發電也是較小程度上的助因。當蒸汽引擎正在發展時，來自磨坊的水力已經為越來越多的工廠、礦場和加工過程供應動能。19世紀末之前，蒸汽動能都未能在經濟效益上媲美當時最好的水車(■2.1)，當中包括已被大大改良的水渦輪機。蒸汽動能最終得以取代水力以至其他動力源，顯然是因為事實證明水力無法驅動船舶！不過水力如何被用作推動機械的技術，其實跟使用蒸汽引擎一樣：槳和曲柄這兩個東西都是未來發展和研發的源頭。

紐科門在1712年製作的引擎，技術上其實不算是蒸汽引擎，但他把它命名為「氣壓引擎」，是依靠冷凝一個充滿蒸汽的氣缸，從而讓大氣壓力將活塞壓下，在衝程的底部，使在水平樑的另一端的配重設計，如圖2.2般將活塞向上拉，並拉動新的蒸汽供應。

把它應用到水泵的運作上是很明顯的（這是蒸汽引擎的第一個用途），因為簡單的泵就是將水經垂直管中吸出。因此，我們從圖2.2可見的，就是一直在航海世界中被沿用直至19世紀末的蒸汽引擎，是「樑（beam）」把移動中的活塞的能量轉移。紐科門用了顯然易見的方式，就像蹺蹺板般，接收一端的引擎活塞的上下移動（技術上稱為「往復運動」），然後在另一端製造等同的上下移動。當被使用於船用蒸汽引擎時，它被稱為「遊樑（walking beam）」，會推動一個曲柄，從而驅動船槳輪的運作。在希明頓於1801年左右為了申請專利而提交的各種動力傳輸裝置的繪製圖紙中，我們可以清楚地看到這個遊樑(■2.3)。直至1880年代，仍然可以在香港、廣州、澳門的小輪上看到它(■2.4)。

幾乎所有初期的蒸汽驅動船，都是利用活塞往復運動轉換成推動船隻螺旋槳的裝置，當中運用了兩種老舊的技術：曲柄和飛輪——後者起初是以明輪的形式出

現，這也是另一種很古老的發明(■2.5)。這完美地示範了在科技變革的過程中，舊主意經常都會出現於新的應用之中，而這種模式將會一次又一次地出現在船用蒸汽動能的發展史上。

不是有誰橫空地發表「哇！為甚麼我不用船槳划水，而是用水移動船槳呢？」只是有人看見水推動水車（一個6,000年前的主意），便可輕易地想像其反方向作用。

似乎所有早期的水車都是平面的，紀錄上首台垂直輪（即第一艘蒸汽船上的那種）分別出現在公元14年的羅馬和同時期的中國。同樣地，最初利用垂直明輪推動船隻的紀錄，亦同時出現於中國漢朝（雖然很可能要到宋朝才真正建造出實體）和羅馬。⁶中國設計的版本有著比較簡單的機制，是一種靠划船夫用腳操作的曲柄。

曲柄是非常古老的設計，早於公元前7世紀地中海一帶，以及200至300年後在中國漢朝（雖然幾乎可以肯定更早時期已被發現）已有紀錄。你在圖2.6及2.7可以清楚看到，並從圖2.5可以推斷出，曲柄有助於把來自手或腳的往復運動變為旋轉運動，或者相反地以其他方式把旋轉運動變成往復運動(■2.6)。在第一台蒸汽引擎出現的時期，曲柄的多重應用十分普遍。16世紀一本德國手冊展示了曲柄在機器中的45種用途⁷，此外你亦能夠想像出更多用法。

其次，飛輪或有著相同用途的東西，都是能夠應付划槳過程中，往復式推動臂在拉力轉為推力之前的能量流失——任何有踩過單車的人都知道，當我們的腳踩在腳踏的頂部或底部時，那種既不是拉又不是推的感覺。飛輪的動量（儲存的能量）消除了往復臂的顛簸震動並在理論上提供了一個穩定的驅動力。這個主意隱含在漢代中國的揚谷機的風扇中（以吹走稻米的糠和外壳）(■2.7)。

問題是所有使用紐科門設計的初期蒸汽引擎當應用到船上時，注定只能是有限的成功，甚至是昂貴的挫敗。原因是引擎體積巨大、低效，而且並非十分有力——

除非跟原本的馬力或人力比較。此時所需要的，是重大的技術和工程上的突破。

這就是為甚麼由1712年到1802年登打士(Charlotte Dundas)的成功，需時近一個世紀；第一艘橫越大西洋的蒸汽船薩凡納號(■2.8)，亦另外花了16年。然而，從船用蒸汽動能的角度來看，薩凡納號其實是失敗的例子，原因是當時所用的蒸汽引擎依然相當低效，並不乎合成本效益。薩凡納號於1819年從美國喬治亞州的薩凡納(Savannah)航行至英國利物浦的旅程，歷時29天11小時，比起最快一次全程單靠風帆航行還要慢。而且，引擎在旅途中只被使用過80小時，但船隻的燃料在旅程完結前兩日已經耗盡。

類似的故事發生在11年後，即1830年，蒸汽拖輪帆船霍布斯號(Forbes)從印度加爾各答出發，將渣甸洋行運鴉片的快速帆船潔美斯娜號(Jamesina)拖到廣州，成為出現在中國水域內的第一艘蒸汽船(■2.9)。儘管潔美斯娜號在新加坡加油時已盛載了額外的煤碳，但當船隻航行至距離珠江仍有450海里(850公里)時，霍布斯號卻出現燃料短缺的危機，而不得不遺下潔美斯娜號。接下來發生的事，將暴露更多早期航海蒸汽引擎的問題。霍布斯號花了另外整整一個星期的時間完成餘下的旅程，而且大部分時間都只是使用風帆。同樣地也是只使用帆，潔美斯娜號僅比霍布斯號多花兩日時間。由加爾各答出發的整段旅程歷時了38日。僅僅一年後的1831年，打破紀錄的鴉片船紅色漫遊者(Red Rover)只用風帆航行亦用了相同的時間。

首個成功地完全由蒸汽動能驅動的越洋旅程直至1838年才發生，由英國的大西方號(SS Great Western)(■2.10)和天狼星號(SS Sirius)共同達成。即管如此，這也只是未來的小小引子，因為到30多年後，蒸汽船才開始取代帆船，成為全球船舶團隊中的一份子。

這是一場緩慢的征途。在每年貨運量方面，蒸汽戰勝風帆的轉捩點要到1870年代

後期才出現，原因是那時的蒸汽船能更快速和更頻繁地航行。全球蒸汽船的總噸位(即內部容積)則要待1890年代初才超越帆船。不過，談到實際船隻數目，在1910年前依然是帆船比蒸汽船領先。船用蒸汽動能的成功故事歷時逾一個世紀，是一個漫長且緩慢的發展和改革的故事。

第一個蒸汽船的意念似乎出現於1729年的英國，來自一位名為艾倫(John Allen)的醫生。不過，蒸汽船的設計似乎沒有被製造出來，甚至連船是如何驅動都無人知曉。到1736年，赫爾斯(Jonathan Hulls)憑他設計の明輪拖船取得專利。有人質疑過它是否曾經被製造出來，另有一個說法指那是一個失敗的製作。

首台真正能運作的蒸汽船出現於1770年代後期。在1776年的法國，齊弗瑞侯爵(Claude-François-Dorothée, marquis de Jouffroy d'Abbans)的第一艘船巴拉米貝德號(Palmipède)啟航，卻很快就沉沒了。要到7年後的派羅斯卡夫號(Pyroscaphe)才成功下水(■2.11)。兩者都是靠赫爾斯所設計的蒸汽引擎操作旋轉的明輪來驅動，幾乎可以肯定，此靈感是來自於為大多數早期工業機械提供動力的水車。

面對著能力較弱但更具影響力的開拓蒸汽機的法國競爭者，加上法國的政治狀況和社會制度，齊弗瑞在船用蒸汽發展上未曾發揮其應有的影響力。在這個故事裡，我們看到，社會、經濟，以至更廣泛的文化環境，如何在蒸汽技術發展的成功與失敗上發揮關鍵作用。

5 儘管希明頓成功地於1788年測試了第一艘蒸汽動能船，但其法國發明家齊弗瑞侯爵(Marquis de Jouffroy)1783年已經成功製造出蒸汽動能船，1781年美國發明家菲奇(John Fitch)亦已發明了非常低效的船隻蒸汽船「毅力號(Perseverance)」。

6 維特魯威所描述的船槳，是靠牛隻推動的齒輪絞盤操作！

7 勃克勒(G.A. Boeckler)，《新劇院機器(Theatrum machinarum novum)》，科隆，1662。

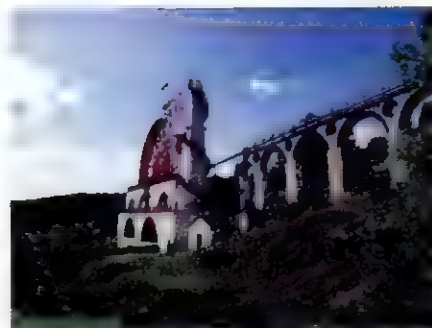


Figure 2.1: The great Lady Isabella waterwheel in Britain's Isle of Man, built in 1854.

(Source: Wikipedia.)

圖2.1：位於萌島的「伊莎貝拉女士」大水車，建於1854年。

(資料來源：維基百科。)



Figure 2.2: A contemporary image of a Newcomen engine.

(Courtesy Science Museum Group Collection © The Board of Trustees of the Science Museum. (Creative Commons))

圖2.2 紐科門引擎的現代畫像。

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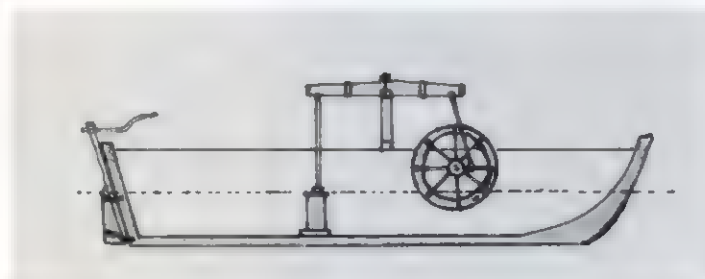


Figure 2.3: For Lord Dundas, No. 3 Steamboat by William Symington — 1801.

(Source: R.H. Thurston, A History of the Growth of the Steam Engine, New York: D. Appleton & Co., 1886, p.380.)

圖2.3：給登打士爵士，威廉·史明頓第三號蒸汽船。

資料來源：雷伯特·亨利·瑟斯頓，《蒸汽機的發展史》。

紐約：艾普頓公司，1886年，第380頁。

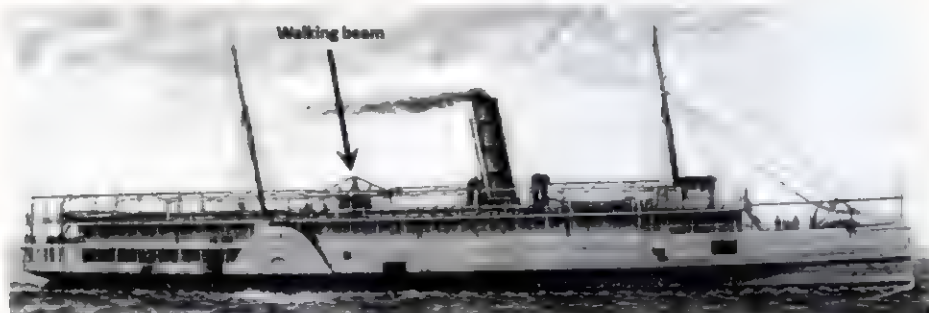


Figure 2.4: The Hongkong, Canton and Macau Steamboat Co. ferry *Honam*, built in Scotland by A. & J. Inglis, Ltd., 1882.

(Source: <http://www.clydeships.co.uk/view.php?ref=10214#v> with additions by SNGD)

圖 2.4：1882 年由蘇格蘭英格利斯製造、香港廣東澳門汽船公司的小輪活南號。
(資料來源：<http://www.clydeships.co.uk/view.php?ref=10214#v> SNGD 修訂版。)

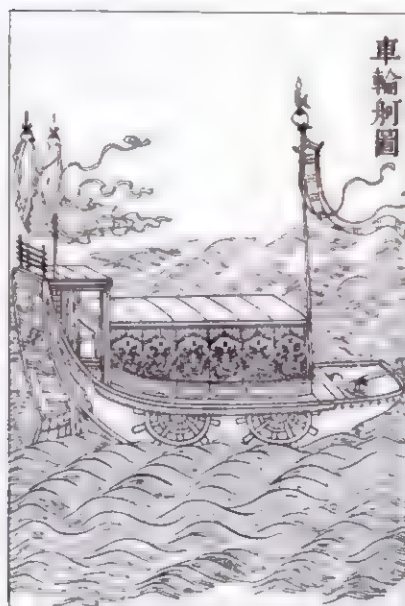


Figure 2.5: A paddlewheel ship from the *Imperial Encyclopedia* (古今圖書集成), the earliest design possibly dating back to the 5th century CE.

(Source: Wikipedia.)

圖 2.5：《古今圖書集成》中的最早出現明輪船設計圖像，可能可追溯至公元 5 世紀。(資料來源：維基百科。)



Figure 2.6: 15th century European idea for hand crank powered paddles. (Source: Wikipedia.)

圖 2.6：15 世紀歐洲手動曲柄式船槳。
(資料來源：維基百科。)



Figure 2.7: Han Dynasty pottery model of a crank operated winnowing machine. (Source: Wikipedia from the Henan Provincial Museum.)

圖 2.7：漢代一台鼓風機由陶製的曲柄操作。
(資料來源：維基百科「河南博物院」。)



Figure 2.8: The first trans-oceanic steamship, the American SS *Savannah*. (Source: Smithsonian Institution.)

圖 2.8：第一艘越洋汽船，美國薩凡納號。
(資料來源：史密森尼學會。)



Figure 2.9: Sunqua (fl. 1830–70), The paddle steamer 'Forbes' off Lintin
(Source: Skinner Auctioneers and Appraisers, Auction: 2295. American Furniture & Decorative Arts, Boston, June 05, Lot: 87.)

圖 2.9：宋呱（活躍時期 1830–70 年）靠在內伶仃島附近的
明輪蒸汽船「雷布斯號」。

（資料來源：Skinner 拍賣行和鑑定人，拍賣編號 2295 美國傢俱及
裝飾藝術，波士頓，6 月 5 日，編號 87）



Figure 2.10: The paddle steamer SS *Great Western*, 1838
(Source: National Maritime Museum, PAH8859)

圖 2.10：明輪蒸汽船大西方號，1838。

（資料來源：國家航海博物館，PAH8859）



Figure 2.11: De Jouffroy's own model of the *Pyroscaphe* —
steam-powered paddles. (Musée national de la Marine, MnM 23 MG 1.)

圖 2.11：費弗瑞的蒸汽明輪船派羅斯卡夫號。

（資料來源：巴黎海事博物館，MnM 23 MG 1。）

3

INEFFICIENT CLOUDS OF STEAM

低效的蒸汽雲

Steam engines, like all engines, are judged in terms of their efficiency. That's a technical way of asking what percentage of the energy in the fuel used to make the steam produces usable power for the engine to pump or to push a ship along.

To begin with there was no clear way to answer that question. Everyone knew that Thomas Newcomen's engine used an awful lot of coal every hour. That was easy to measure in tonnes. The trouble was that there was no way of measuring what that coal consumption meant in terms of the work of pumping that the engine was successfully doing, in order to compare one means of pumping with another.

蒸汽引擎就如所有引擎一樣，會根據其效率被評估。這是一個從技術方面提出的問題：要使蒸汽產生能驅動船隻的動能，其燃料的能量百分率是多少？

其實這個問題是沒有明確答案的。所有人都知道紐科門引擎每小時都消耗驚人數量的煤，那是可以用噸來量度。但問題是沒有方法理解如此大的煤耗量意味著甚麼，無法將這種抽水方法與另一種抽水方法進行比較。

If you think about it, you'll see that an entirely efficient engine would convert 100% of the available energy in its fuel into its output. Of course, thanks to later scientific work, we know that is impossible. But obviously a very inefficient engine would be one that only converted a small percentage of its fuel's available energy. Greater efficiency would convert higher percentages.

The method needed to come up with such numbers was applied mathematics, and it was first used to evaluate the efficiency of waterwheels. That introduces us to another of the fascinating figures in the story of steam, John Smeaton, who is not only famous for being a pioneer lighthouse engineer, but for being 'the father of civil engineering'. Less directly, it also introduces us to the only woman in this story, thanks to the prejudices of the past, the eminent French mathematician Emilie du Chatelet, whose work in the 1740s on what we now think of as the conservation of energy was widely influential. In the early 1750s Smeaton was interested in the same issue, and put his thinking to practical use.

Smeaton was interested in calculating the comparative power of a waterwheel worked by water passing underneath it, and the same waterwheel worked by passing water over the top of it (Fig. 3.1). He came up with a way of quantifying and calculating the difference accurately, which showed conclusively that the overshot waterwheel is the more powerful. That is, it used more — a higher percentage — of the available energy contained in the flowing water than the undershot wheel did.

James Watt, the great hero of the steam engine, used a similar approach to Smeaton's to provide the answer to evaluating the comparative power of a steam engine. Borrowing from Thomas

Savery, Watt developed the idea of comparing a steam engine with what had always provided the power for lots of machinery, the horse. He asked himself how many horses would be needed to provide the same amount of power that a steam pump could provide, and how to measure it and called his answer an engine's horsepower (HP) (Fig. 3.2).

We needn't worry about the precise details, but with his unit of measurement, Watt was able to tell the clients who wanted to buy his engines how many horses an engine would replace.⁸ And once there was a measure of an engine's output in horsepower, it was possible to assess the engine's cost efficiency in terms of either another engine with a horsepower rating or, of course, continuing to use horses. Watt's clients knew how much coal cost and how much either a rival make of engine or the cost of stabling and feeding a horse cost, so they could work out whether buying and running a 10 horsepower Watt engine was more or less expensive than buying and running someone else's engine or buying and keeping 10 horses.

The earliest steam engines were inefficient. They were not very powerful, but they were very big and burned a lot of coal. The earliest developed only about five horsepower, and burned 32 lbs (14.5 kg) an hour for every horsepower, or nearly two tonnes of coal a day. These days we know it was only about 0.1% efficient. The waste of energy only made sense for owners of coal mines, where coal was very cheap, and for owners of mines where a reliable 24/7 pump, even if expensive, could earn its keep.

Here James Watt gave the steam engine another useful term, which he labelled its 'duty', or how many pounds of water an engine could pump out of a mine by burning one bushel of coal.⁹ With a way of working out efficiency, a

comparative unit of power and a measure of effective work, potential owners could calculate comparative costs fairly simply.

The main efficiency problems for early steam engines were engineering ones. Too much of the coal's energy was lost because the design of the boilers, based on a simple pot on a stove, was inefficient — we'll come back to that in Chapter 7. More heat was lost because the pipes and cylinders were not insulated. In addition, because joints didn't fit well and the piston didn't fit tightly in the cylinder, too much steam escaped and did no work. Early engines were surrounded by clouds of escaped steam, and we'll deal with the basis of how that was solved in the next chapter.

At this point we need to focus on how the steam engine worked once it had achieved its basic form in the first engine of James Watt. We'll keep it simple.

Water is boiled in an enclosed vessel. For every one cubic centimetre of water, the resulting steam occupies about 1,649 cubic centimetres — much more space than the original water (Fig. 3.3). This steam passes through a pipe into a cylinder sealed at the top by a piston. A valve on the inlet pipe closes, cutting off the steam and the exhaust valve in another pipe leading to the condenser opens. The steam in the cylinder starts condensing back into water as it rushes from the cylinder into the condenser. This creates a near vacuum in the cylinder and condenser because the condensed steam occupies 1,649 times less space, which results in the piston being pushed down by the air pressure acting on its outside surface. The top of the piston is connected by a rod to one end of a pivoted beam or a crank. When the piston moves down, it pulls the crank or end of the beam after it. The exhaust valve is then closed and the inlet valve

is opened. Either the momentum of a flywheel or a counterweight at the other end of the beam pulls the piston back up, sucking more steam into the cylinder... and the whole sequence is repeated again and again and again for as long as the boiler provides steam.

The main problem in the development of the steam engine was that to begin with the whole thing depended on the difference in pressure between the inside and the outside of the cylinder once the steam had condensed. If the piston didn't fit well in the cylinder, then air could rush in round the edges of the piston to replace the condensed steam. This drastically reduced the difference in pressure between inside and outside the cylinder, and with it the efficiency of the engine.

It follows that the story of the steam engine before it went to sea is the story of trying to improve its efficiency by reducing all the losses of heat on the one hand, improving the whole system's pressure tightness on the other and, above all, shrinking the whole engine to manageable proportions. Only when those problems had been solved would a truly effective marine steam engine be possible.

James Watt's major breakthroughs were four: one was to give his engines a separate condenser. Up to that point the steam in the Newcomen engine cylinder was condensed back to water by opening a valve and letting in a jet of water cooling the cylinder down, causing the steam to condense. Then a valve was opened to let the water out before shutting it off and opening the inlet valve to let more steam in. By condensing the steam outside the cylinder, Watt helped keep the cylinder hot, which was very important. Along with another of his inventions, a pump driven by the same beam to improve the vacuum in the

condenser, it helped increase the power of the piston stroke.

Watt's second breakthrough was to realise that his engine's efficiency would be increased if the cylinder did not lose heat through its walls, so that again the difference in temperature between cylinder and condenser should be as big as possible. He solved the problem by giving his cylinders a hollow jacket through which the steam passed on its way to the cylinder.

The third key, development — like an awful lot of technological improvements — didn't come from the world of pumps and engines at all. It came from a man called John Wilkinson, who made cannons for the British Navy. Wilkinson had worked out that the reason 18th century cannons were not very accurate and, now and then, burst when they were fired, killing or maiming the gun's crew, was because of the way they were made.

The problem was that gun barrels were made by casting them with a core in the mould so that the resulting hollow cylinder just needed machining to smooth out the inside of the barrel. The problem was that the central core wasn't always exactly centred or exactly the same diameter throughout its length. Shooting was inaccurate because the gas from the exploding gunpowder could escape around the cannon ball, making the range unpredictable. And because the barrel only fitted the cannon ball exactly here and there, the ball did not always go exactly where it was aimed. Worse, because the barrel was cast around a core, there was another problem: the complex mould meant that the resulting cooled metal often had flaws, which were weak points. Because of the huge pressures in barrels when they were fired, especially if the barrel also had an uneven wall thickness because of an off-centre core, the

outcome was that barrels burst too often.

John Wilkinson, learning of a secret Dutch technique based on the Swiss Jan Maritz's invention of 1747, accepted that a better way, which would result in more consistent quality metal and equal thickness walls to the barrel, was to cast the gun barrels as a solid mass and then drill out the barrel with a precision machine tool (Fig. 3.4). The result of the design he came up with in 1767 was more accurate and more reliable guns.¹⁰

Up until James Watt turned to John Wilkinson, all the cylinders of early steam engines had been made by bending iron plates into a curve and riveting them together to create the cylinder. That meant the cylinders were never truly cylindrical and pistons never fitted exactly, leading to the loss of both steam and pressure. James Watt realised that his cylinder problem could be solved by using Wilkinson's technique. John Wilkinson promised Watt a cylinder that would be true throughout its length to the thickness of an English shilling, which was 1/10th of an inch (or about 2.5mm). This was incredibly precise for any object of large-scale engineering in the late 18th century. The shift to increasing precision that Wilkinson introduced was itself a key breakthrough in the story of steam, and it was connected to two very important developments in creating machinery like steam engines, which are often overlooked and which we shall look at in the next chapter.

We'll come back to Watt's fourth development in more details later, but to finish this chapter we can say that what he saw, in contrast to Newcomen, was that rather than letting the atmosphere do the work pushing down the piston when the steam condensed, the engine could be designed so that incoming steam did the work. That

resulted in the first 'dual action' or 'double-acting' steam engine of 1782, in which the steam filled first one side, then the other side of the piston (Fig. 3.5). For the first time, steam on one side and a vacuum on the other did all the work, though efforts to make the whole system more and more pressure tight continued. More importantly, with the new engine what's called the power-to-weight ratio, which had improved to offer more power with less engine and boiler weight, resulted in the first steam engine that would be small and powerful enough to propel a vehicle... or a ship.

We can now look at what all such improvements depended on.

- 8 Watt's calculation was that a horse could pull a 550 lb (249 kg) weight 60' (18.3m) up into the air in one minute, so any engine that could do the same was a 1HP engine. If it could pull 3,300 lbs up to the same height in the same time, it would be a 6HP engine. Today the horsepower has been replaced by a standard international unit for measuring power called the Watt, in honour of James Watt: 1 HP = 745.7 watts
- 9 A bushel is an old British unit for measuring the volume of dry bulk substances like grain, sand, ores or coal. One pound (1 lb) = 0.454 kg, 1 bushel = 36.4 litres = c.48.9 kg of coal.
- 10 The Swiss Jean or Johan Maritz (1680–1743) is the first to use a vertical boring technique at the French Royal Foundry in c.1713, a horizontal drilling system was later perfected by Maritz and the Dutchman Jan Verbruggen (1712 – 1781) in 1747. It was Verbruggen's horizontal lathe that Wilkinson learned of and copied, and that he adapted for use to bore engine cylinders.

你可以幻想，一個完全有效的引擎，可以百分百把煤的可用能量轉化為其功率。當然，多得往後的科學研究，讓我們知道這是不可能的。但很明顯，低效引擎只能轉化煤的可用能量當中非常小的百分比；越高效就能轉化越大百分比的可用能量。

要得出這樣的數字，需要用上應用數學——亦是它首次用以計算水車的效率。在此，蒸汽故事中一個引人注目的人物斯密頓（John Smeaton）登場了。他不只因燈塔工程先驅而聞名，也是因為他的「土木工程師之父」的身份而為人熟知。我們亦曾見故事唯一一位女性（由於那個年代的偏見）、大名鼎鼎的法國數學家沙特萊侯爵夫人（Émilie du Châtelet）出場。她在1740年撰寫關於我們今日眾所周知的節約能源的文章，影響力十分廣泛。1750年代初，斯密頓亦對同一個問題感興趣，並將其想法付諸實行。

斯密頓的興趣是精確地計算出水從水車下面流過和從上面流過所產生的能量的分別（■3.1）。他想到一個方法，可以精準地量化和計算出兩者的不同，結果發現上射式的水車能夠產生最大力量。也就是說，相比起下射式水車，它能使用流水中最多（百分比最高）的可用能量。

蒸汽引擎的大英雄瓦特使用與斯密頓類似的方式，提供計算和比較不同蒸汽機效率的方法。瓦特參考了沙維利（Thomas Savery）的主意，想出更進一步的想法，就是將蒸汽機與其他同樣常用於為機械提供能量的事物（例如馬匹）作對比。他問自己，需要多少匹馬才能提供與蒸汽泵同額的能量，而我們可以怎樣測量它。他把這量度方法稱為引擎的馬力（縮寫為HP）（■3.2）。

我們毋須進入那些精確的細節，但使用其量度單位，瓦特就能夠告訴那些蒸汽引擎的準顧客，一部引擎能夠取代多少匹馬。⁹一旦可以衡量引擎的馬力輸出，我們就能以此評估引擎的成本效率——比較另一台具定額馬力的引擎，或是繼續以馬匹作動能。瓦特的客人便能夠知道他需要使用多少煤，以及製造一台引擎還是餵飼並訓練一隻馬的

成本較高；亦能夠計算出購買並操作一台10馬力的瓦特引擎會否比購買其他生產商的引擎昂貴，還是購買並馴養10匹馬的成本較高。

最初期的蒸汽引擎是非常低效的，它們的功率非常低，而且極之巨型並消耗大量煤。最早的引擎只有5馬力，但每馬力每小時會燃燒32磅（14.5公斤），即每日近兩噸的煤！此時它們的效率大約只有0.1%！這種程度的能量耗費，只有煤礦主人才負擔得起——因為有便宜的煤供應。另一種情況，即便煤很昂貴，只要煤礦主人擁有一台可靠且全天候運作的泵亦能達至收支平衡。

同時瓦特亦給予蒸汽引擎一個很好用的術語，他稱為「能率（duty）」，即一部引擎每燃燒1蒲式耳的煤，能從礦井中泵起多少磅水。有了計算效率的方法、比較功率的單位，以及有效工作的標準，用家就能夠以較簡單的算術計算和比較成本。

早前蒸汽引擎的主要效率問題是工程問題，因為鍋爐的設計十分低效——單靠爐上一個鍋，煤的能量損耗太多。這個我們在第7章會再詳細討論。加上管和氣缸並不隔熱，導致更多煤的熱能流失。而且由於接駁口不完善，活塞未能緊密地安裝在氣缸內，以致過多蒸汽洩漏而未能發揮作用。這些蒸汽的流失讓早期的引擎看上去總是被一堆雲覆蓋，我們下一章就會談到人們解決這個問題的基礎。

現在先聚焦於在第一代瓦特蒸汽機達至基礎模式後，蒸汽引擎是如何運作的。我會講得簡單一點。

水在封閉的容器中被燒滾。每1立方厘米的水所產生的蒸汽約佔1,649立方厘米——所佔的空間比它原本的大很多（■3.3）。這些蒸汽穿過管道進入頂部用活塞密封的氣缸；進入管道的氣閥關上，蒸汽被截斷，管道另一端、連著冷凝器的排氣閥打開；蒸汽從氣缸衝入冷凝器時，氣缸裡的蒸汽開始冷卻變回水。這在氣缸和冷凝器中製造了一個近乎真空的環境，原因是冷卻的蒸汽所佔的空間會縮小1,649倍。這導致活塞被其表面的大氣

壓力推低。活塞頂部是以小棍連接著旋轉槓或曲柄的一端。當活塞向下移，它會拉動曲柄或槓的末端。然後，排氣閥關閉，進氣閥打開，不論是飛輪的動量還是槓的另一端的配重，把活塞拉後，並把更多的蒸汽吸進氣缸……整個過程一次又一次地發生——只要鍋爐供應蒸汽。

蒸汽引擎發展的主要問題是——一旦蒸汽冷卻後，整個過程的開始就依賴氣缸內外的壓力差。如果活塞體積不準確、不能合適地裝嵌在氣缸，那麼空氣就會跑入活塞邊緣周圍並取代了冷卻的蒸汽，這樣便大大地減低了氣缸內外的壓力差，令引擎的效率大減。

瓦特有四點重大的突破。首先他為引擎設計了一個分離的冷凝器，當紐科門引擎的氣缸打開閥門，讓水噴進從而冷卻氣缸，蒸汽便冷凝變回水。然後閥門被打開，讓水流再關閉，進氣閥就打開並讓更多蒸汽進入。透過冷凝氣缸外部的蒸汽，瓦特保持了氣缸的熱力，這非常重要。加上他的另一個發明，用同一個槓驅動的泵改良冷凝器內的真空狀態，幫助提升活塞衝程的效率。

瓦特的第二個重大突破是，他意識到若減少熱力從氣缸壁流失，就能提高引擎的效率，此舉亦令氣缸和冷凝器之間的溫度差距盡量擴大。為解決這個問題，他為氣缸設計了一個中空의 保溫套，讓蒸汽可以穿過它到達氣缸。

第三個關鍵發展——一如很多技術改良——根本不是來自泵和引擎本身的領域，而是來自一位名為威爾金森（John Wilkinson）的人，他是為英國海軍製造大炮的。他發現18世紀的大炮不太精準，偶爾在發射時甚至會爆炸引致槍隊隊員傷亡，原因在於人們製造它的方法。

問題在於鑄造炮管的模具核芯，中空的圓柱體只需要用機器把管的內壁加工至平滑即可。問題是中間的核心並不總是精確地置中或直徑長度完全相同。那就意味著，不準確的發射是由於爆發的火藥所產生的氣體可能會在炮彈周圍洩漏出來，使射程難以預測。同時，因為炮管只能剛好放入炮彈，而

炮彈不能準確地射到瞄準的地方；更差的是，因為炮管是藉由管芯鑄造，這便衍生了另一個問題。複雜的模具意味著所得的冷卻金屬經常附帶瑕疵，那就是炮管的薄弱點。開炮時炮管內的極高壓力——尤其是因核芯的偏離導致炮管壁的厚度不平均——所產生的結果，就是炮管經常爆炸。

威爾金森參考了一項基於瑞士人揚·馬里茨（Jan Maritz）在1747年的發明的荷蘭秘密技術，想出一個更好的、可以製造出質素更一致的金屬和厚度更平均的炮管壁的方法，就是把炮管先鑄造成堅硬的金屬塊，然後使用精密的機床鑄出炮管（■3.4）。憑著1767年的設計，他生產出更精確和更可靠的槍炮。¹⁰

由瓦特到威爾金森，所有早期蒸汽引擎的氣缸都是以屈曲鐵板，並把它們銲接在一起而製成的，即是那些氣缸從來都不是真正的圓柱形，活塞與之亦從來不能完全相合，因此過程中會流失很多蒸汽和壓力。瓦特認知到這問題可以用威爾金森的技術來解決，威爾金森向瓦特承諾，可以造出一個整個長度都只有一個英國先令厚度（即1英吋的十分之一，約2.5毫米）的氣缸。這在18世紀後期，於任何大型工程來說都是極其地精準的。把精確度提升到威爾金森所提出的程度是一個轉捩點，同時亦是蒸汽機突破的關鍵，它與製造如蒸汽引擎的機械方面兩個非常重要的發展有關，但總是被人忽視。這留待在下一章再詳述。

至於瓦特的第四個開發亦將在稍後詳述。不過，在這一章完結之前我想說的是，不同於紐科門，在蒸汽冷凝的過程中，瓦特的設計讓進入的蒸汽（而不是大氣壓力）把活塞壓下。因此才有了1782年的第一台雙作用（或稱雙動）蒸汽引擎，這種蒸汽機的蒸汽會首先填充活塞的一邊，然後才進入另一邊（■3.5）。這是首次蒸汽在一邊而另一邊以真空推動所有操作，儘管使整個系統越來越緊壓的改良還持續中。更重要的是，新引擎的功率重量比改進了，能提供更多的能量且引擎和鍋爐的重量更少，令到引擎可以做

得更細小且更功率更大，足以推動汽車……甚至船隻。

現在來看一下，所有上述改進所依賴的東西。

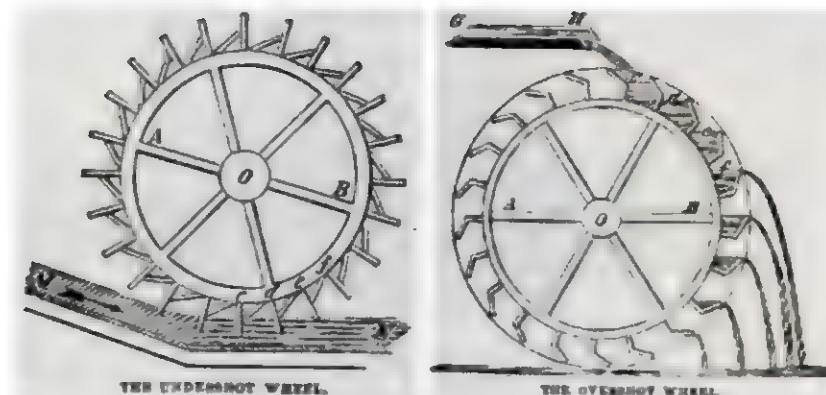


Figure 3.1: Undershot and overshot waterwheels.
(Source: *Philosophical Transactions of the Royal Society*, vol 51, 1756)

圖3.1：下射型水車與上射型水車。
(資料來源：英國皇家學會《自然科學叢刊》，第51卷，1756年。)

- 8 瓦特(Watt)的計算是，一匹馬可以在一分鐘內將550磅(249.5公斤)重的東西向上拉60英尺(18.3米)，所以任何可以做到這一點的引擎都是1馬力的引擎。如果可以在同一時間將3,300磅的重量拉到相同的高度，則是6馬力的引擎。如今，馬力被稱為「瓦特」的標準國際單位取代，1馬力 = 745.7瓦，以紀念瓦特。
- 9 蒲式耳是測量大量穀物、沙子、礫石或煤炭等乾燥物質的古老英式單位。1磅 = 0.454公斤，1蒲式耳 = 36.4升 = c.48.9公斤煤。
- 10 瑞士人吉恩(Jean)或約翰·馬里茨(Johan Maritz)(1680–1743)在約1713年法國皇家鑄造廠率先使用垂直鑽孔技術，後來馬里茨和荷蘭人簡·維布魯根(Jan Verbruggen)(1712–1781)於1747年完善了水平鑽孔系統。威爾金森學習並複製了維布魯根的臥式車床，並將其改裝用於發動機氣缸的鑽孔。

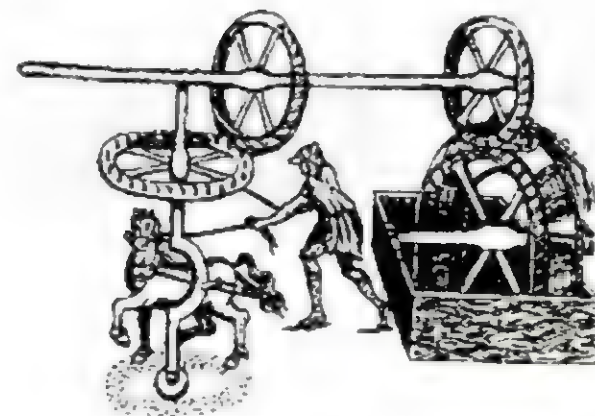


Figure 3.2: A one horsepower water pump.
(Source: <http://www.johnhearfield.com/Wind/Windmills.htm/>.)

圖3.2：一馬力的水泵。
(資料來源：<http://www.johnhearfield.com/Wind/Windmills.htm/>。)



Figure 3.3: Steam occupies hugely more space than the water boiled to create it.
(Source: SNGD.)

圖 3.3 蒸汽所佔空間比產生它們的沸水要大得多。
(資料來源: SNGD。)

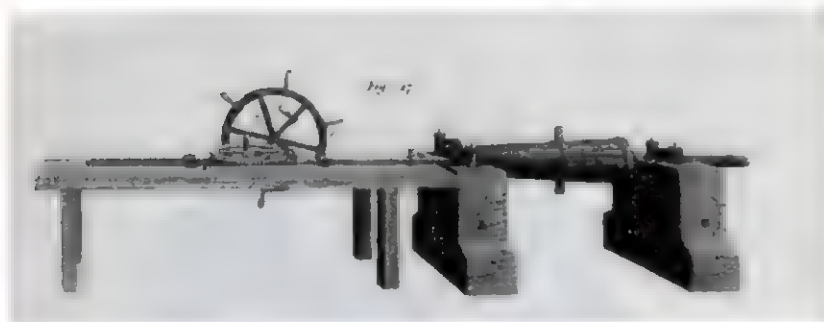


Figure 3.4: John Wilkinson's cannon boring jig.
(Source: Abraham Rees, *The Cyclopaedia; or, universal dictionary of arts, sciences and letters*, Plates vol. 2, Plate III, fig 17, (Wilson Lowry, Jnr), London: Longman, Hurst, Rees, Orme & Brown, 1820)

圖 3.4: 威爾金森的大炮鑽床。
(資料來源: 亞伯拉罕·里斯,《百科全書》, 或《藝術、科學和字母通用詞典》, 第2版III, 圖17(威爾遜·洛里·約翰內斯), 倫敦: 朗文、赫斯特、里斯、奧姆利布朗, 1820年。)

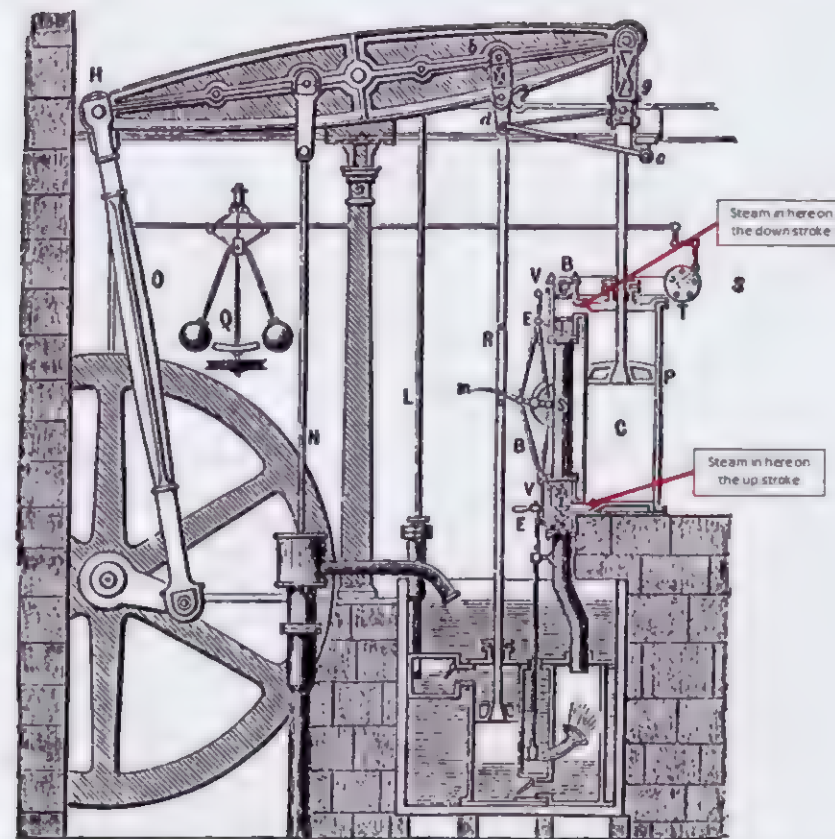


Figure 3.5: Watt's dual action engine of 1782.
(Source: R.H. Thurston, *A History of the Growth of the Steam Engine*, New York: D. Appleton & Co., 1886, p.119)

圖 3.5: 瓦特在1782年的雙動式引擎。
(資料來源: 羅伯特·亨利·瑟斯頓,《蒸汽機的發展史》, 紐約: 艾普頓公司, 1886年, 第119頁。)

4

精確測量與 繪圖的藝術

THE ART OF MEASURING AND DRAWING PRECISELY

Almost all early technology was a matter of making things by eye using whatever materials were available. That doesn't mean things were not well and carefully made, as we can see from the many wonderful and beautiful objects from the past that have survived, like the graceful jointing of a Ming dynasty chair (Fig. 4.1).

差不多所有早期的技術，都是手眼配合，利用任何可用的物料來製作，但並不代表這些物件做得不好或者很隨意，正如我們所見，從前很多美好而漂亮的器物依然保存至今，例如以下精緻地拼合的明朝椅子（圖4.1）。

But a consequence of this way of making things was that each example of whatever it was ended up being unique. It was *like* all the other examples, but it was never exactly the same, never *identical*. The differences were seldom great, perhaps only a few millimetres, but they were always there because that is how craftsmen work when they make things by eye.

The connections are loose but, during the 15th and 16th centuries, changes in how artists and others pictured the world formed an indispensable context for the emergence, in the late 18th century, of what became an essential feature of the development of the steam engine: the scale engineering or technical drawing. Without it, the precision and replicability — the ability to make an exact copy of something — of steam machinery could not have happened.

Using drawings as explanatory tools was already an established element in most high cultures, for example in China, in a practice that went back to the Song Dynasty and perhaps before to Song Yingxing's (宋應星) *Tiangong Kaiwu* (天工開物) of 1637. What marks the 18th century in Europe is the evident attempt, using the best artistic techniques, to produce exact rather than 'more-or-less-like-this' drawings of the objects discussed and, where possible, scale drawings. A wonderful example is the great multi-volume *Encyclopédie* of Frenchmen Denis Diderot and Jean Le Rond d'Alembert.¹¹ This was innovative.

Until the late 18th century the artisans in Europe who produced early machinery worked, as we know their peers in China did, by building scale models. But by the end of the 18th century, the need for precise instructions to be communicated in a clear and economical way between designer and

mould-maker, foundryman, machinist or builder took this sort of drawing in a new direction. This was the introduction of technical or engineering drawings that would eventually show every detail of a given machine using what soon became widely shared conventions (Fig. 4.2). Today's CAD digital tools are their direct descendants.

This development depended on a wider habit of representationally exact perspective drawing that we can trace back to the pioneering, 11th century *Book of Optics (De Aspectibus)* of the Arab theorist known in the West as Alhazen (Abū 'Alī al-Ḥasan ibn al-Ḥasan ibn al-Haytham), translated into Latin in 1200. This was directly related to early 16th century Italian Renaissance architects' use of scale drawings to guide their work, allied to the development in 16th century Europe, initially in a military context, of increasingly precisely measured two-dimensional plans of fortifications, not long later of buildings, estates and towns and, in the 17th century, ships. We see all this very clearly in the work of the great Leonardo da Vinci. By the last half of the 18th century in Europe, very precise perspective and plan drawings of all sorts of things had become a key part of how machinery was explained both to artisans and to an interested public.

Whilst the evidence is not complete, it would seem likely that a key contribution was by James Watt, this time in conjunction with his partner Matthew Boulton. Boulton and Watt appear to be the first of whom we have record who used what are recognisably modern-style engineering drawings to make sure that the engines they made (Fig. 4.3), which were always assembled on the site where they were going to be used from parts made in a number of different places, were put together correctly.¹² This is how iPhones are put

together in Shenzhen from designs made in the USA and parts made in 43 countries!

In 1765, two decades before Boulton and Watt began producing the drawings the correct building of their engines needed, a Frenchman called Gaspard Monge, a mathematician and engineer, could be said formally to have established the technique of technical or engineering drawing.¹³ In his system of descriptive geometry, Monge gave engineers the tool they needed to be able to communicate precisely. The key was a specific set of procedures that a draughtsman had to follow to represent a three-dimensional object in two dimensions. Today we call this the orthographic projection (Fig. 4.4). It gives us the standard views we see in any engineering drawing: the plan (a bird's or worm's eye view), the elevation (a view from any one of four sides) and a derivative of the two, the cross-section (a plan or elevation of a slice through an object).

Like so much of the story of steam, tucked in behind the emergence of the vital scale drawings is another equally important set of developments. As a short cut we can reduce this to standardisation in measurement and the creation of the tools to do the precision measuring — the centuries-long process that has given rise to today's SI system, and the precision of modern machine tools and measuring and laboratory instruments.¹⁴

Everywhere in the world, deciding on the length, width or height of something began by referring to units of measure that related to our bodies. The earliest we know of is the cubit, roughly the distance between the elbow and the end of the middle finger, which appears in Egypt in what is known as the 18th Dynasty (1550–1292 BCE). There were

always efforts to standardise such measures. In China, for example, these are first attributed to Yu the Great (大禹) in the third millennium BCE, with a standardised decimal system set up by the first emperor of a unified Chinese state, Qin Shi Huang (秦始皇), in the 3rd century BCE. Such efforts usually failed because someone can always gain an advantage by using a different value... and nothing ever succeeded in preventing that happening. That is why establishing measurement standards remained characteristic of every new dynasty in China, as it did at similar moments in almost every other ordered society we know about.

However, in Europe as of the 17th century something began to change. It is very hard to identify exactly why and what, but a new sort of interest in all the amazing variety of systems of measurement that had existed in the past and continued in use, how they had arisen and how and if they were related to each other was an important factor. More important though was the emergence of more effective, centralised governments and their bureaucracies, what we now call science and its foundation in systematic experiment, on the rapid development of military technology, especially the cannon and fortifications designed to resist it, and on the expansion of sea trade and its requirements for more and more precise navigation. Effective government was needed systematically and reliably to enforce any standards. But that needed social impetus to ensure it was complied with, which is what seems to have happened. It was very soon realised that any experiment, to have credible results, had to be based on exact and replicable quantities. Militarily, making war or creating reliable defences relied similarly on consistent measurement. And with

sea voyaging, knowing the dimensions of the earth and the distances between any two points on it became vital for planning and executing voyages and avoiding shipwreck once any voyage was underway.

By the mid-18th century, when the steam engine was about to go through an important step change in the work of James Watt, most European nations had established national standard units of measurement. The extent to which such units were actually used varied hugely, as was the case with most pre-modern societies. But where the instruments of scientific experiments, navigation, the machines of warfare and the new industries were concerned, exact measurement had come to matter greatly, as we saw with John Wilkinson's boast that he could machine iron to plus or minus 2.5mm.

At this point we can cut a long story short and assume that there is an agreed and generally enforced local set of standard measurements. That allows us to focus on two key aspects: how precisely we should measure anything and how we can be sure that anyone who measures the same thing comes up with the same value on every occasion the same measurement is made.

Almost every aspect of the new world of scientific experiment and innovative engineering had a simple answer to the first question. We should measure whatever we are measuring as precisely as our means of measurement allow. The ideal, of course, was to measure absolutely exactly. But that leads us straight to a core problem: the means — the instrument that did the measuring.

For most of human history where measuring mattered — and for most of the time in most societies, in terms of exact quantity it didn't much —

measuring instruments, where they existed, had to be made by hand. That meant their scale had to be made by someone copying another handmade scale as exactly as possible. That had two consequences for the accuracy of the resulting instrument: inevitably, the coordination of hand and eye being what it is, no handmade measurement instrument was without errors. Secondly, there were obvious limits to sub-division. A scale in centimetres is fairly easy to make by hand. A scale in millimetres is more challenging. A scale in tenths of a millimetre is impossible without high-quality magnification. A scale in hundredths of a millimetre is impossible. Today, in contrast, modern microchips for computers are manufactured to a scale of millionths of a millimetre. Look at Figure 4.5 to see what that means... and what today's almost unbelievable — certainly impossible to visualise — improvements to what is meant by precision measurement mean.

Like so much of engineering history, the apparent breakthroughs in the 18th century that were to be so important to the development of the precision engineering on which the steam engine depended had very old roots. The keys here were two things: the lathe, an instrument that can be traced back to the second millennium BCE in Egypt, and the screw with its thread.

In 1639 a man called William Gascoigne invented a measuring machine — today we would call it a micrometer (Fig. 4.6). He made it using a hand-operated lathe to cut a very fine screw thread to move a measuring device. The scale of the device was on a round plate on one end of the screw that divided one full rotation of the screw into 10 parts. It followed that one tenth of the number of threads for a given length of screw was the minimum length that

could be measured. Gascoigne's screw had thirty-three threads per inch (25mm), so could in theory measure to a precision of $1/330^{\text{th}}$ of an inch (or 0.076mm) (Fig. 4.7). Whether it actually could, however, depended on how accurately the screw thread had been cut. Until the last half of the 18th century, the answer was that, as with engraving measurement scales, thread cutting mainly by hand-assisted machines could not be as accurate as Gascoigne's measuring machine needed it to be.

With such instruments, if their screw threads were exact, it became possible to measure things with a precision that had never before been possible. In 1772 a tabletop version of what has become today's micrometer was invented by none other than James Watt, of whom it has been said, "without Watt, a history of micrometers cannot be written."

But that is to jump ahead a bit, because another key element in the rapid 18th century advance in the precision of measurement was the invention of machines that could exactly cut screw threads and that could precisely engrave radial scales (scales on the circumference of a circle) of the sort micrometers use.¹⁵

Jesse Ramsden was an ingenious man who came up with the answers. He made the first modern screw-cutting lathe in 1775, a device on the accurate products of which he was able to base his greatest invention. This was his ingenious 'dividing engine' that for the first time cut accurate radial scales without the imperfection of hand/eye coordination (Fig. 4.8). As with everything else we have considered, both the screw-cutting lathe and the dividing engine of 1777 were major improvements of preceding machines and ideas. Ramsden, genius though he was, stood on the shoulders of others.

By the beginning of the 19th century therefore, thanks to the work of people like Monge, Ramsden, Smeaton and Watt — and there are many, many others whose names have not been mentioned — makers of steam engines had the resources they needed constantly to improve their machines.

- 11 The *Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers* (Systematic encyclopedia or dictionary of sciences, arts and occupations) was produced between 1752 and 1771 in 17 volumes of text and 11 of illustrations.
- 12 A lovely book showing the emergence of this vital art is Ken Baynes' and Francis Pugh's, *The Art of the Engineer*, Guildford: Lutterworth Press, 1981
- 13 Monge was one of the founders of what became France's famous Ecole Polytechnique.
- 14 SI stands for 'Système international (d'unités))' from the French, and is known in English as the International System of Units which was established in 1960 based on efforts to create an international system of standard units of measurement that goes back to the dawn of the steam age.
- 15 For the maritime world this was vital, because such scales were indispensable if accurate sextants and protractors were to be made.

這樣的造物方式，令到每一件被造出來的物件都是獨一無二的，它們跟其他器物相像，但從來都不是一模一樣。那些差異不會很大，也許僅僅是幾毫米，但就總是有所不同，因為這就是工匠用肉眼製作器物時的效果。

縱然兩者的連繫不太明顯，但在15和16世紀期間，藝術家和其他人描繪世界方式的轉變，為18世紀後期蒸汽機的發展造就了不可或缺的環境。這就是工程或技術比例繪圖。缺少了它們，蒸汽機器的精確性和可複製性（精確地複製某些東西的能力）就不可能實現。

在大多數高雅文化中都會利用繪圖作為說明工具，例如在中國，甚至可追溯至宋代，1637年宋應星的著作《天工開物》或更早期。18世紀的歐洲，更明顯地嘗試使用最佳的藝術技巧為論述對象製作精確而非「差不多」的圖像，並盡可能繪製比例圖。舉個完美的例子，就是法國人狄德羅(Denis Diderot)和達朗伯特(Jean Le Rond d'Alembert)革新的多卷大百科全書¹¹。此舉是創新的。

在18世紀下旬之前，歐洲早期的機械工匠，就如在中國的同行人般，是透過製作比例模型來完成工作的。但到了18世紀末，由於設計師需要以清晰和經濟的溝通方式向模具工匠、鑄造工、機械工、建築工等發出準確的指示，因此這種繪圖方式就成為了新的方向。這就是技術和工程繪圖的序曲，它最後更會透過迅速被廣泛使用的手法，詳細展示特定機械的細節(圖4.2)。而它更是我們今天的CAD(電腦輔助設計)數碼繪圖工具的鼻祖。

此發展有賴於精確透視法繪圖的廣泛使用，而這種繪圖方式可追溯至11世紀的阿拉伯理論家海什木(Abū 'Alī al-ḥasan ibn al-ḥasan ibn al-Haytham，通常在西方被稱作Al Hazen，中文譯作「海桑」)的開創性著作《光學之書(De Aspectibus)》，此書在1200年被翻譯為拉丁文。這直接連繫到16世紀意大利文藝復興建築師使用比例

繪圖協助工作，亦與當時歐洲的發展相關，這些越來越精準地量度的平面設計圖最初是用於軍事用途，譬如防禦要塞，不久延伸至建築物、莊園、城鎮，以至17世紀的船舶。我們從達文西的作品中可以清晰地看到這種應用。到了18世紀下旬的歐洲，所有精確的透視和平面圖，已成為向工匠和感興趣的大眾解釋機械的關鍵部分。

儘管證據還不完整，但瓦特這次與他的搭檔布爾頓(Matthew Boulton)似乎作出了重要貢獻。布爾頓和瓦特似乎是有紀錄以來首批人，以現代風格的工程繪圖(圖4.3)，來確保他們製造的引擎組件被正確地組裝在一起——因為這些組件並非在同一個地方製造。¹²這與iPhone把在美國設計，於43個不同國家或地區製造零件，卻在深圳組裝的方式如出一轍。

早在1765年，即瓦特和布爾頓開始製作精確繪圖的20年前，一位名為蒙日(Gaspard Monge)的法國數學家兼工程師，可以說已經正式發展出技術或工程繪圖的技巧。¹³在其投影幾何(descriptive geometry)學的系統中，蒙日為工程師提供了他們能夠進行精確溝通所需的工具，關鍵是一套繪圖員必須遵從的具體程序，讓他們能夠以二維方式表達三維的對象。這方法在今天被我們稱為正射投影(orthographic projection)(圖4.4)。它為我們提供了在任何工程繪圖中都能看到的標準視覺：平面圖(鳥瞰圖或仰視圖)、正視圖(從四個側面中的任何一個側面看)以及兩種剖面圖(對象的平面或立面的切面圖象)。

就像蒸汽故事背後有比例繪圖的出現，比例繪圖後亦有另一個同樣重要的發展。我們可以將此簡化為測量法的標準化、精確測量工具的創立——經過幾個世紀才發展出今天的國際單位制度(SI system)，以及現代機械工具、測量和實驗室儀器的精密度。¹⁴

在世界上的任何地方，要確定某物的長度、寬度、高度，最初都是以我們的身體作為度量單位。我們最早知道的是出現於埃

及第18王朝(公元前1550-1292年)的腕尺(cubit)，大約是手肘與中指末端之間的距離。要統一這些量度標準十分艱難，以中國作為例子，最早可歸功於公元前3000年的大禹，並由公元前3世紀、首個統一中國的皇帝——秦始皇，建立了標準化的十進制制度。這樣的嘗試通常徒勞無功，因為總有其他人用別的量度單位取而代之，無人能阻止這種事發生。所以中國每次改朝換代都要確立一次度量衡，而當時其他地方有秩序的社會亦經歷差不多的事。

然而，在17世紀的歐洲事情開始有所轉變，儘管難以言明這些轉變是甚麼和為何出現，但當時一個新關注點尤其重要，就是已發明並繼續被使用的各種測量系統是怎樣產生，和如何互相關連(如有)。更重要的是，當時出現了更有效的中央集權的政府及官僚體制、我們今天稱為科學的東西及其基礎(即系統化的實驗)、軍事技術(尤其是槍炮以及用以防禦這些槍炮的工事)的急速發展，加上上海貿易的擴張，以及其所衍生對更精準導航的需求。要有系統和可靠地執行任何標準，都需要有效的政府，亦需要社會推動力來確保它有得到遵守，而這似乎已經發生了。人們很快意識到，任何實驗若希望得到可信的結果，都須要建立在精確且可複製的數量之上。軍事——無論是引發戰爭還是作防守——也相類似，都依賴貫徹一致的測量。至於航海，了解地球的範圍及其上任何兩點之間的距離，對於計劃和實行航程，以至在航行過程中避免海難，都變得相當重要。

到了18世紀中，在瓦特正替蒸汽機的設計踏出重要的一步時，大多數歐洲國家已經發展出國際標準的量度單位。就如大多數前現代社會一樣，在使用這些不同單位時的差別其實很大。不過，測量精準度對那些科學實驗導航儀器以及戰爭和新興工業的機械都極重要，威爾金森亦因此可以自誇將鐵加工打磨成正負2.5毫米。

至此長話短說，假設已經有一套有共識並普遍實行中的量度準則，那麼我們就

可以集中討論兩個關鍵部份：量度物件時我們究竟需要去到多精密？以及如何確定每個人在每次量度同一物件時都會得出相同的數值？

在科學實驗和創新工程的新世界裡，都會對第一個問題有個簡單的答案。在許可的範圍內，我們應該把要量度的事物，量度工具能量得有多準確就多準確，理想當然是量度到完全精準，然而這就直接指向核心問題：工具——我們用以量度的儀器。

在大多數重視測量(卻不在乎精確)的人類歷史中測量的儀器都需要由人手製造，意味著它們的尺度必須盡可能複製另一個手作的尺度。這就使儀器的精密產生兩個結果。首先，靠手眼協調的手工製作測量儀器無可避免地帶有誤差。其次，在畫出細分刻度上有明顯的限制。厘米刻度還算易於用手製作，到毫米就很具挑戰性了；如無高品質的放大技術，就不可能做到十分之一毫米的刻度，而百分之一毫米的刻度則根本不可能。相比之下，今天電腦用的微晶片已經可以造到百萬分之一毫米。細看圖4.5您就會明白那是什麼意思，以及今天幾乎是難以置信的改進了對精準測量的含義(當然是絕不可能被視覺化)。

就如大多有關工程的歷史，在18世紀出現了明顯的突破，對日後蒸汽引擎所高度依賴的精密工程發展十分重要。關鍵在於兩點：車床(一種可以追溯到公元前2000年的工具)，以及帶螺旋紋的螺絲。

一位名為威廉·加斯科因(William Gascoigne)的男子在1639年發明了一台測量機器，今天我們稱之為測微計(micrometer)(圖4.6)。他以手動的车床割出非常精確的螺紋，以推動一測量裝置。此裝置的刻度是在螺絲末端的一個圓形碟上，並把旋轉一周分割為10等份。因此，就特定長度的螺絲，其螺紋長度的十分之一就是可量度的最小長度。加斯科因的螺絲每英吋(25毫米)有33條螺紋，所以理論上能夠量度到三百三十分之一英吋(或0.076毫米)的精確度(圖4.7)。可是，能否做到實則取

決於螺紋的切割精確度。答案是，直到18世紀後半葉，主要由手動機器切割、有雕刻刻度的螺紋，並不能夠如加斯科因的測量機所需那般精密。

有了這些儀器，如果它們的螺紋是精準的，物件的精度就可以變得前所未有地準確。桌式測微計於1772年出現了，發明者不是別人，正正是瓦特，當時還有人說「沒有瓦特，就無法書寫測微計的歷史。」

而18世紀測量精確度急速發展的另一個關鍵因素，是有人發明出一台能夠準確切割螺絲螺紋，且能精確地刻出放射形刻度（在圓周上的刻度），以供測微計使用。¹⁵

心靈手巧的拉姆斯登(Jesse Ramsden)就是關鍵人物。他在1775年製造出首個切割螺絲的車床，讓他可以在這精

細的製成品之上造出更偉大的發明。這就是創新的「分割引擎」，讓人第一次不受手眼協調的缺陷影響，切割出了精確的放射形刻度（圖4.8）。就如前述的其他創見，無論螺絲切割車床或是1777年的分割引擎，都是對前人的機械和理念的重大的改進。拉姆斯登無疑是個天才，但他也只是站在別人的肩膀上。

因此，有賴蒙日、拉姆斯登、斯密頓、瓦特，以及許多沒有被提及的名字，到了19世紀初，製作蒸汽機的科技人員有其所需的資源去不斷地改良他們的機械。

11 《百科全書，或科學、藝術與工藝詳解詞典(The Encyclopédie ou Dictionnaire raisonné des sciences, des arts et des métiers)》共17卷文本和11張插圖，於1752年至1771年間製作。

12 一本可愛的書——貝恩斯(Ken Baynes)和普格(Francis Pugh)的《建造的藝術(The Art of the Engineer)》(吉爾福特：拉特維斯出版社，1981)展示了這種至關重要的藝術的誕生。

13 蒙日是後來法國著名的巴黎高等理工學院的創辦人之一。

14 SI代表法文的「Système international (d'unités)」，即英文的「International System of Units」，即國際單位制，此制度成立於1960年，有賴蒸汽時代致力創立一套國際標準度量衡單位制度的努力。

15 對於航海世界而言，這一點極為重要，因為若要製作精確的六分儀和量角器，這種比例尺是必不可少的。



Figure 4.1: The exquisite carpentry of a Ming dynasty chair.
(Source: Christie's, An extremely rare and important pair of huanghuali horseshoe-back armchairs, quanyi, Ming dynasty, 17th century, Fine Chinese Ceramics & Works of Art Auction, 7 November 2017.)

圖4.1：木工精美的明朝椅子。
(資料來源：佳士得，一對極為罕有而重要的黃花梨馬蹄形扶手椅，明代，17世紀，中國瓷器及藝術品拍賣，2017年11月7日。)



Figure 4.2: A technical drawing of a small ship from the great French Encyclopedia — note the scale in French feet (pieds).
(Source: University of Chicago online copy at <https://encyclopedia.uchicago.edu/>)

圖 4.2 《百科全書》中一幅顯示一艘小船的技術繪圖，
比例單位是法國英尺（土瓦茲）。

，資料來源 芝加哥大學在線副本，網址為<https://encyclopedia.uchicago.edu/>。）



Figure 4.3: One of James Watt's technical drawings for parts of a steam engine, 1785.
(Source: Museums Victoria, <https://collections.museumvictoria.com.au/items/407748/>)

圖 4.3：瓦特的其中一幅蒸汽引擎組件的技術繪圖，1785 年。

(資料來源 維多利亞博物館 <https://collections.museumvictoria.com.au/items/407748/>)

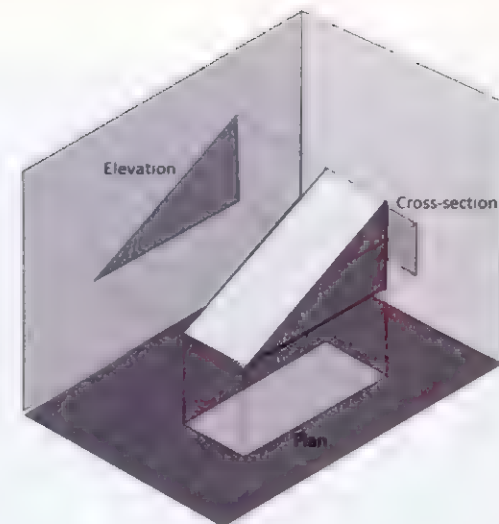


Figure 4.4: An orthographic projection.
(Source: SNGD.)

圖 4.4：正影投射。

資料來源 SNGD。)

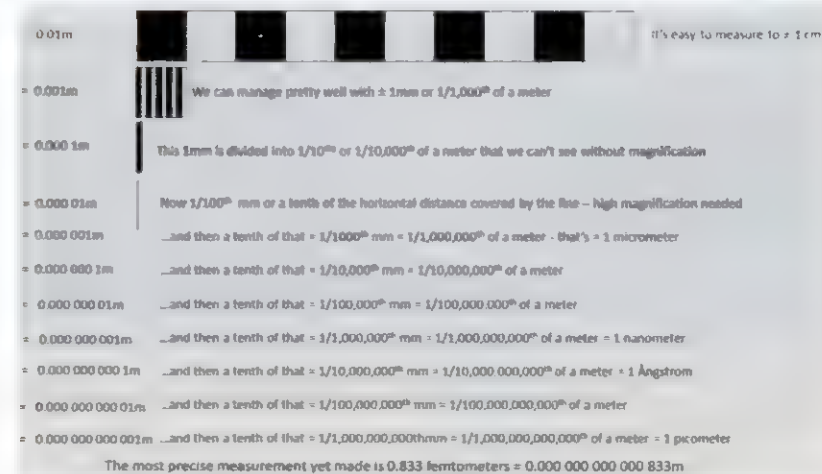


Figure 4.5: How what we mean by precision measurement has changed.
(Source: SNGD)

圖 4.5：我們對於精準測量的定義的改變。

(資料來源 SNGD・)

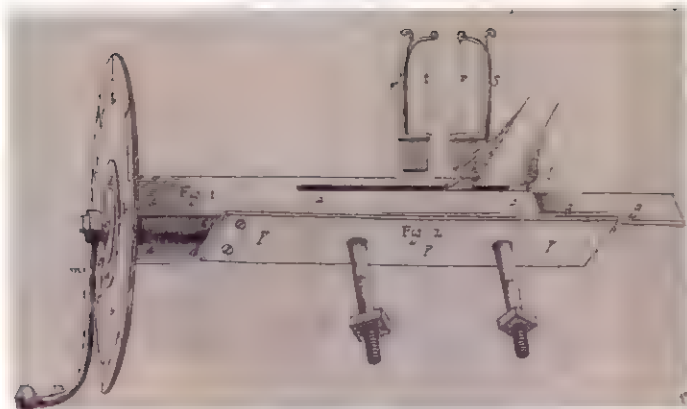
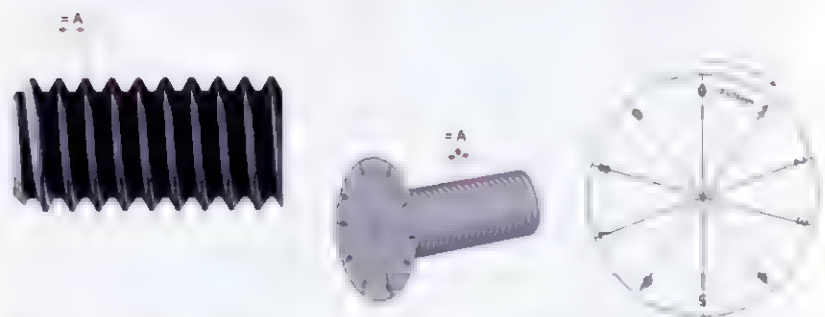


Figure 4.6: Robert Hooke's drawing of Gascoigne's "Instrument for Dividing a Foot into Many Thousand Parts", 1667.

(Source: detail from Robert Hooke, *A Description of an Instrument for Dividing a Foot into Many Thousand Parts, and Thereby Measuring the Diameters of Planets to a Great Exactness, &c. as it Was Promised*, Philosophical Transactions of the Royal Society, vol. 2 29, 1667)

圖 4.6：羅伯特·虎克所繪畫加斯科因的《把一英尺分割成數千份的儀器》，1667。
(資料來源：羅伯特·虎克的詳細資料：《一機將一英尺分成幾千個部分的儀器的描述，把行星的直徑如承諾般量度至最準確》皇家學會自然科學會報 第229卷 1667年。)



Rotate the screw one full turn and it travels distance A
So looking at a disc with ten divisions fastened to the end of the screw, as the screw moves distance A, the disc rotates from 0 to 0 measuring in tenths of A
If A=0.76mm, then each division of the disc = 0.076mm

Figure 4.7: How Gascoigne's screw micrometer worked.
(Source: SNGD)

圖 4.7：加斯科因的螺絲測微計的運作。
(資料來源：SNGD。)



Figure 4.8: Jesse Ramsden's dividing engine.
(National Museum of American History, MA 215518)

圖 4.8 拉姆斯登的分割引擎。
(資料來源：美國國家歷史博物館 MA 215518)

5

船槳與螺旋槳

PADDLES AND SCREWS

We have seen how the first efforts to harness steam engines to propel boats and ships used the paddlewheel. Based on very old technology, it was an obvious way to turn reciprocating into rotary motion to drive something forwards. It is no coincidence, therefore, that around the same time that inventive minds were using paddlewheels to harness a steam engine to propel a boat, they were also thinking of using the same mechanism to drive wheels to propel land vehicles — steam boats and steam trains spring from a common root (Fig. 5.1).

我們已經看過首批試圖利用蒸汽引擎產生動力並透過明輪驅動船隻的艱辛努力，是基於一種古老的技術，把往復運動的動能轉化為旋轉運動，以驅動物件向前進的方式。因此，那些創造力也在相同時期構想出以明輪推動蒸汽引擎從而驅動船隻，及至利用相同的機械原理推動輪子以令陸地上的汽車行走，完全不是巧合——汽船和汽車的有著相同的起源（圖 5.1）。

The paddlewheel was the first solution because, as the standard ways of powering small craft by paddles or oars showed, they were the obvious way to transmit power from a vessel floating on the water to pull or push it forwards.

The problem was, for complicated reasons we don't need to go into, that all such means of propulsion only actually push a vessel forwards over the short distance when the blades are close to right angles to the water. So, whilst a rotating wheel on land can be expected to travel the distance of the wheel's circumference along the ground for each revolution, that wasn't true of paddles. A ship moved only about 40–60% of the paddlewheel's circumference. Worse, paddlewheels were especially inefficient, if used at sea, when the sea got rough and the ship rolled from side to side and pitched from end to end. When that happened, the paddles were at uneven depths in the water, unlike in the smooth water of a canal, river or lake, and lost even more of their push (Fig. 5.2).

Almost from the first where the application of the steam engine to boats and ships were concerned, people puzzled over how to create an entirely submerged means of propulsion always pushing the boat in one direction. Again, the basic ideas that eventually provided the path to the preferred solution were very old and had nothing to do with ships or the sea!

One unquestioned inspiration was a water pump that perhaps goes back to Babylon (in modern day Iraq) in the 8th century BCE, although today, for various reasons, it is most commonly attributed to the 3rd century BCE Greek called Archimedes. As with waterwheels inspiring paddlewheels by getting them to work the other way, so with the Archimedean screw. In the pump the screw stayed in one place, rotated in

the water and pulled the water upwards (Fig. 5.3).

But what if the screw were free to move so that, like a wooden screw being driven into a piece of wood, it could pull itself forward through the water? As we shall see, that was the idea that was first used.

If that was one line of thinking, another is said to have been brought back to Europe from China around 1780. An important figure in 18th century British naval architecture, Colonel Mark Beaufoy, is said to have seen a model of a Chinese propeller, possibly a horizontal wind-powered vane brought back to Europe as one of the many items that returned in the East Indiamen in the Canton Trade. Such impellers using rising hot air are said to have been common in China since at least the Tang and possibly the Han dynasty. An inventive mind like Colonel Beaufoy's — he devised the first tank testing for ship hulls — could easily have seen how such a device was exactly like a cross-section of a multiple-turn Archimedean screw.

The most likely Chinese example, however, was an even older equivalent to the windmill called the *zhuqingting* (bamboo dragonfly, 竹蜻蜓), either carved from bamboo or made of bird's feathers (Fig. 5.4). This marvellous children's toy dates back to the Warring States era in the 5th century BCE and is said to have arrived in Europe in the 15th century, although any intelligent observation of sycamore or lime tree seeds falling through the air demonstrates the same idea. It is always a mistake to succumb to the "My daddy got a car before your daddy" theory of history. Parallel invention by ingenious human beings wherever they are is a much more probable answer to the origin of any idea rooted in everyday experience.

However, we do know that the

bamboo dragonfly inspired 19th century work in Europe on helicopters and airscrews. It follows that in the 18th century it could clearly have provided a similar inspiration to anyone trying to come up with a way of 'screwing a ship through the water'. The *zhuqingting* works, after all, by 'screwing itself up into the air'.

Whatever the actual source of the idea, by the 17th century in Europe successive thinkers were proposing one or other sort of screw propeller. One of the first that actually hit the water as opposed to being an idea on paper was the American inventor David Bushnell's *Turtle* of 1776. Appropriately, it was a weapon in America's War of Independence from Britain, and thus a revolutionary craft in more than merely one sense. It was not only a very early example of a working submarine — technically a submersible because it mainly travelled with part of it above water — used in combat but had one of, if not the first, hand-driven propellers.¹⁶

The *Turtle's* propeller, designed by the wonderfully named watch and clock maker from New Haven, Connecticut, Isaac Doolittle, is remarkable because, rather like de Jouffroy's steam engine, it could have shortcut this aspect of making steam power work at sea. However, the *Turtle* was lost when the ship carrying it was sunk by the British and, it seems, Doolittle's interesting idea was lost with it for more than half a century (Fig. 5.5).

The most radical idea for propulsion at this time appeared a decade later, also in America, although the first patents for similar ideas date from the 17th century in Britain: a water jet. In 1787 James Rumsey solved the problem of providing sufficient propulsive pressure by using a steam engine to drive a pump that sucked sea water in at one end and

forced it out at the other. But solving the energy loss problems of water jet propulsion was beyond the technology of the day with its inefficient steam engines and crude engineering, and Rumsey's experimental vessel only managed a speed of 1.73 knots (3.2 kmh).¹⁷

The paddlewheel therefore remained dominant until 1835, when Francis Pettit Smith filed the first patent for what would become the modern screw propeller (Fig. 5.6).

Smith's idea worked, but wasn't easy to fit to a ship, as you can see from Figure 5.5. What was needed was something that made the propeller more compact, which was what happened in the independent work of Swedish American Captain John Ericsson, to whom the invention of the modern propeller is credited (Fig. 5.7a & 5.7b).

But like almost everything in our story, correctly understanding how a propeller actually worked needed the efforts of scientists to identify and solve the complex problems of what would become the new science of hydrodynamics, so that more efficient propellers could be made. The breakthrough was by a British engineer called Robert Griffiths, who in 1849 patented what became the basic form of all subsequent propellers (Fig. 5.8), although explaining why it worked would have to wait for the theoretical work of W.J.M. Rankine, Alfred George Greenhill and R.E. Froude between 1865 and 1889.

By the 1840s, however, sufficient trial-and-error advances had been made for one of the most famous moments in the story of steam at sea to occur. It happened in 1845, when the British Royal Navy was persuaded that it should trial the comparative performances of paddles and a propeller by using two identical ships powered by the same type and power of engine. Two naval

steam frigates, HMS *Alecto*, powered by paddles, and HMS *Rattler*, powered by a screw propeller, engaged in a number of comparative trials. The most famous was when they were tied stern to stern and then worked up power in opposite directions (Fig. 5.9).

There is some argument about how truly equal the trial was, but as far as the world was concerned the result — backed by several other different trials between the two ships — showed that the screw propeller was the way forward for steam propulsion.

The *Rattler* was the first warship in the world to be powered by a propeller, and 10 years later — from 1855–1856 — was part of the Royal Navy's China Squadron in Hong Kong. You can go and see a memorial to some of its sailors, called the Kuhlan (Gaoian, 高欄島)

Monument, in the Hong Kong Cemetery. They were killed in an action against pirates, in company with the USS *Powhatan*, a paddle frigate, near Macau on 4th August, 1855. The steam engine was a critical weapon in the fight against piracy on China's coast in the 19th and 20th centuries.

With the invention and development of the propeller, the marine steam engine had an efficient means of transmitting its power to move a ship. However, two other developments would be needed before steam power captured the maritime world and revolutionised global trade: more efficiently made steam at higher pressures and a suitable type of ship. We can now turn to the first of them, the ship in which the engine was installed.

明輪是首個解決辦法，因為正如由槳葉或船槳推動的小船提供動能的標準方式所示，它們是從漂浮在水面上的船隻傳遞動能，以拉動或推動前進的明顯方式。

問題在於所有這些推進的方式，其實都只是在於船槳葉片與水面幾乎成直角時，才把船隻推進很短的距離——其複雜的理由我們毋須深究。因此，當在陸地上車輪每旋轉一圈便會沿地面行進圓周的距離，對於船槳來說卻並非如此。船隻只會前進約明輪圓周的40–60%，更糟的是，明輪用於海上特別低效。當海面波濤洶湧而船隻左右顛簸並前後搖晃傾斜時，不像在運河、河流、湖泊等平靜的水平上，船槳會處於不平均的水深，於是便失去更多的推動力。(圖5.2)。

幾乎自從將蒸汽引擎應用於船隻上開始，人們就苦苦思索如何創造一種完全在水底下並一直將船推向一個方向的推進方式。最終的解決方案再次來自非常古老的基本意念，且與航海無關！

其中一個無容置疑的靈感來源，大概可追溯至公元前8世紀的巴比倫（今日的伊拉克），儘管基於種種原因，被普遍地歸功於公元前3世紀的希臘人阿基米德（Archimedes）。與水車透過其反向操作來啟發明輪的發明一樣，阿基米德式螺旋抽水機也是如此。在此系內，螺旋軸被固定在一個位置，在水中旋轉從而把水帶向上（如圖5.3）。

可是，如果螺旋軸不是固定的話會怎樣呢？就像木螺絲被鑽進一塊木頭，它在水裡能否把自己向前推進？就如我們所見，這就是在使用上的最初想法。

如果那是一種思路，那麼另一種思路據說是在1780年左右從中國帶到歐洲的。18世紀英國海軍建築一個重要的人物博福上校（Colonel Mark Beaufoy）據稱見過一個中國螺旋槳的模型，可能是水平式風能葉片——東印度人在廣東貿易中帶返歐洲的眾多物件之一。這種葉輪靠著上升的熱空氣來運作，據說最少在唐朝甚至可能早在漢朝的中國已非常流行。以博福上校所具備的發

明家腦筋（他為船體設計了第一個油箱測試裝置），很容易就能看出這個裝置正正與多圖式阿基米德螺旋抽水機的切面圖相類似。

然而，最有可能的中國例子，是更古老的、類近於風車的竹製或羽毛製玩意，叫做「竹蜻蜓」（圖5.4）。這種奇妙的玩具在中國可追溯至公元前5世紀的戰國時代，而傳到歐洲則據知是公元15世紀的事——儘管任何聰明人觀察過無花果樹或青檸樹種子從空中飄下，其實都能想出這主意。盲從於「我比你更早發明…」這種歷史論述是錯誤的。若果說任何意念皆紮根於日常經驗，我們更應該相信無論身在何處，靈巧的人類都能夠同時並行發明各種事物。不過我們當然知道，竹蜻蜓為19世紀歐洲直升機和螺旋槳的開發提供了靈感。由此可見，早在18世紀它大概已經啟發過某些希望找到方法「把船隻旋出海」的人了，畢竟竹蜻蜓的運作方式是「把自己旋飛到空中」。

不管這個想法的真正根源是甚麼，到了17世紀的歐洲，接連不斷有思想家提出不同種類的螺旋槳構思。其中一個脫離紙上談兵，真正下水的先驅，是美國發明家布希奈爾（David Bushnell）1776年的海龜號（*Turtle*）。正確來說它是英國在美國獨立戰爭中的武器，因此它是多重意義上的革命性技術。它不只是很早期用作戰鬥的在役潛艇的例子（技術上它是潛水器，因為只有部分露出水面航行），更是第一艘以手動螺旋槳操作的潛艇。¹⁶

海龜號的螺旋槳（設計者是個來自美國康乃狄克州紐黑文、有個極好名字的名鐘錶工匠——杜雷（Isaac Doolittle））十分出色，因為它有點像齊弗瑞侯爵的蒸汽引擎，在這範疇可讓蒸汽動力更有效率地運用於海上。不過，海龜號失了蹤，因為運載它的船隻被英國人擊沉了，這讓杜雷的有趣意念似乎也隨之而消失了逾半個世紀（圖5.5）。

這段時期關於推進力最激進的想法出現於10年後，亦是在美國，雖然類似意念的首個專利可追溯至17世紀的英國：噴水推進器。魯塞（James Rumsey）於1787年

16 There are earlier examples, but they were purely experimental and never put to use.

17 The first working waterjet is credited to Italian Secondo Campini in 1931, but material shortcomings meant a limited lifespan. New Zealander William Hamilton's waterjet of 1955 is the accepted pioneer, though he built on earlier ideas of American Keenan Hanley, who had adapted his company's 1930s fireboat water hose pump to act as a jet drive.

利用蒸汽引擎令水泵一端吸入海水並在另一端噴出，來提供充足的推進壓力，以解決問題。可是，基於當時的低效蒸汽引擎和粗糙的工程技術，要控制噴射推進時所產生的能量流失，超出了當時的技術範圍。而魯塞的實驗船隻只能做到1.73節（每小時3.2公里）的速度。¹⁷

因此，明輪依然佔主導，直至史密斯（Francis Pettit Smith）於1835年為日後的現代螺旋槳註冊首項專利（圖5.6）。

史密斯的想法是可行的，但並不容易應用於船上，就如圖5.5所示。螺旋槳需要更緊實，而美籍瑞典裔船長艾力臣（John Ericsson）的獨立研發就改良了這一點，所以現代螺旋槳的問世都歸功於他（圖5.7a, 5.7b）。

可是，就如我們故事裡的其他部分一樣，要正確了解螺旋槳如何運作，始終要靠科學家努力去辨別和解決那些後來演變成流體動力學的新科學當中的複雜問題，才能製作出更有效率的螺旋槳。突破點來自於英國工程師葛利菲斯（Robert Griffiths）在1849年為隨後所有螺旋槳基本款的设计註冊了專利（圖5.8），雖然也要待1865年到1889年間蘭金（W.J.M. Rankine）、格林希爾（Alfred George Greenhill）、弗魯德（R.E. Froude）等人完成他們的理論工作，才得以解釋它是如何運作。

到了1840年代，足夠的反覆實驗帶來了進展，使得蒸汽航海故事裡其中一個最著名的時刻誕生了。1845年英國皇家海軍被說服利用由一樣的引擎所推動的兩艘同款船隻，測試船槳和螺旋槳的相對性能。兩艘海軍蒸汽巡防艦，以短船槳推動的阿萊克托號（HMS *Alecto*）和以螺旋槳推動的響尾蛇號（HMS *Rattler*）進行了多項對比試驗。其中最著名的，是它們以船尾對船尾互相綁著，然後往相反的方向開動（圖5.9）。

關於這次試驗是否真正公平是有爭議的，但世界所關注的試驗結果（這一結果也得到了這兩艘船以外其他幾次不同試驗的支持），顯示螺旋槳為蒸汽推進技術找對了方向。

響尾蛇號是世上第一艘以螺旋槳推進的戰船，而在10年之後（自1855年—1856年起），它是香港皇家海軍中國中隊的一部分。若你到香港墳場（跑馬地墳場）的話，可以看到一塊紀念響尾蛇號士兵的紀念碑，稱作高欄島紀念碑。他們是於1855年8月4日，與槳式巡防艦波瓦坦號（USS *Powhatan*）結伴在澳門附近一次對抗海盜的行動中被殺死的。在19世紀、20世紀，蒸汽引擎是打擊中國沿海海盜的重要武器。

隨著螺旋槳的發明與發展，船用蒸汽引擎能以有效的方法來傳遞推動船隻的動力。不過，蒸汽動能若要佔領航海的世界並讓全球貿易產生革命性改變，還需要兩項發展：更高壓和更有效地製造蒸汽，以及適合的船種。我們先看第一項裝有引擎的船。

16 有更早的例子，但它們僅是實驗性質，從未被使用過。

17 第一台能夠運作的水力噴射器於1931年出現，歸功於意大利人卡皮尼（Secondo Campini），但由於材料短缺，意味著其使用壽命有限。新西蘭人漢密爾頓（William Hamilton）1955年所製的水力噴射器則被公認為先驅。儘管他只是借鑒了美國人漢利（Keenan Hanley）早期改裝了其公司1930年代消防船上以軟水管泵作為噴射推動器的意念。

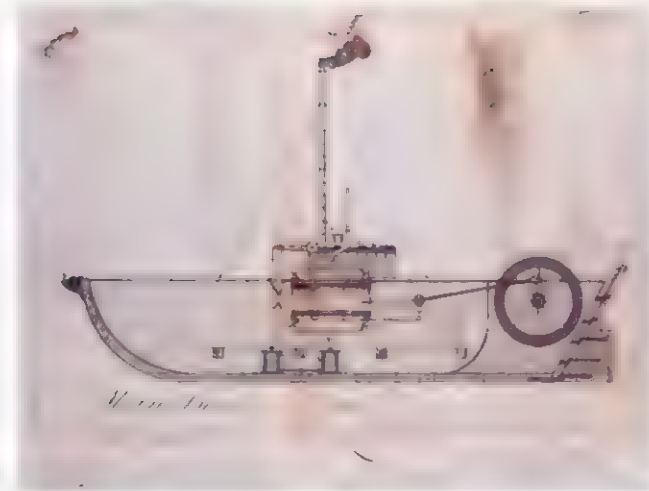


Figure 5.1: A cross-section of the *Charlotte Dundas* her engine and paddlewheel as drawn from memory by William Symington.
(Source: Museums Victoria, Item ST 41084. Engineering Drawing — William Symington, 'Charlotte Dundas', Steam Boat Invented for Lord Dundas, 1801–1803. (creative commons licence))

圖5.1：夏洛特·登打士號引擎和明輪的橫切面圖，由希明頓憑記憶畫出。
（資料來源：維多利亞博物館，項目ST 41084，工程繪圖——威廉·希明頓，夏洛特·登打士號為登打士勳爵發明的蒸汽船，1801–1803年，（創用CC授權修改。）



Figure 5.2: A paddlewheel has 'slip' that means that for each rotation it propels a ship forward less than its full circumference.
(Source: SNGD.)

圖5.2：一個「滑移」了的明輪，即它每旋轉一周，船向前推動的距離小於其整個圓周。
（資料來源：SNGD。）

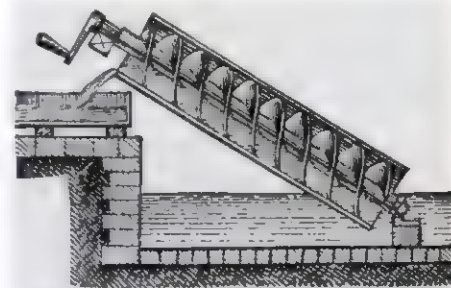


Figure 5.3: An Archimedeal screw pump.
(Source: William Dwight Whitney, *The Century Dictionary, an Encyclopedic Lexicon of the English Language*, New York: The Century Co., 1902, 1:297)

圖5.3：阿基米德式螺旋抽水機。
（資料來源：威廉·德懷特·惠特尼，《世紀詞典 英語百科詞彙》，紐約：世紀出版社，1902年，第一冊，第297頁。）

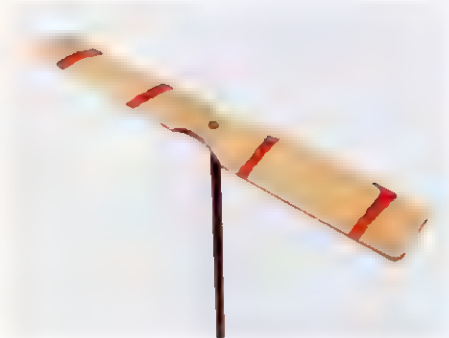


Figure 5.4: A *zhuqingting* or bamboo helicopter.
(Source: Wikipedia Creative Commons.)

圖 5.4：竹蜻蜓。
(資料來源：維基百科。)

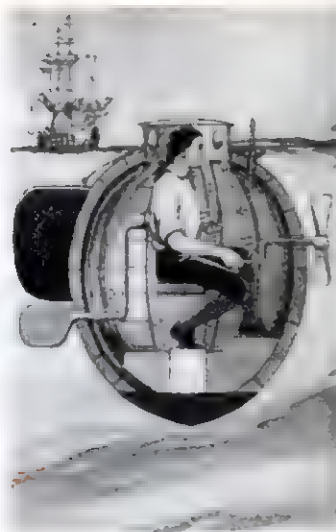


Figure 5.5: David Bushnell's *Turtle* with Isaac Doolittle's hand-driven propeller.
(Source: Wikipedia creative commons from Oceanographic Museum, Monaco.)

圖 5.5：布希奈爾的海龜號用上杜雷的手動螺旋槳——大多數圖像錯誤地繪畫成了阿米德螺旋。

(資料來源：摩納哥海洋博物館的維基百科。)



Figure 5.6: Francis Pettit Smith's original patent drawing of his propeller.
(Source: Francis Pettit Smith's "Specification, A.D. 1836, May 31. No. 7104".)

圖 5.6：弗朗西斯·佩蒂特·史密斯的螺旋槳原始專利圖。
(資料來源：弗朗西斯·佩蒂特·史密斯《規格，公元 1836 年，5 月 31 日，第 7104 號》。)



Figure 5.7a: Ericsson's first patent propeller of c.1836.
(Sources: UK Patent, Specification, A. D. 1836, July 13. No. 7149.)

圖 5.7a：艾力臣第一個註冊專利螺旋槳，約 1836 年。
(資料來源：英國專利，規格，公元 1836 年，7 月 13 日，第 7149 號。)

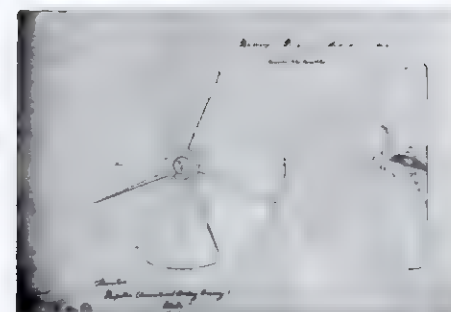


Figure 5.7b: The propeller he designed for the radical USS *Monitor* in 1862.
(Sources: <https://deadconfederates.com/2010/10/10/monitors-screw/>.)

圖 5.7b：他在 1862 年為美國海軍莫尼特號 (USS *Monitor*) 設計的螺旋槳。
(資料來源：<https://deadconfederates.com/2010/10/10/monitors-screw/>。)



Figure 5.8: The propeller patented by Robert Griffiths in 1855.
(Source: Science Museum, Model in brass, scale 1:12, of an adjustable pitch screw propeller, Robert Griffiths patent, No. 92, A.D. 1853 & No. 319, A.D. 1858, Havre, France.)

圖 5.8：格里菲斯於 1855 年獲得專利的螺旋槳。
(資料來源：科學博物館，可調節螺旋槳的黃銅模型，比例 1:12，露伯特·格里菲斯的專利，第 92、AD1853 和 319 AD1858 號專利，法國阿弗爾。)



Figure 5.9: The *Rattler* tows the *Alecko*.
(Source: National Maritime Museum, Greenwich, object PY0923.)

圖 5.9：響尾蛇號拖動了阿萊克托號。
(資料來源：格林威治國家海洋博物館，物件 PY0923。)



木、鐵和鋼

WOOD, IRON AND STEEL

Quite by accident — as is so often the case in the history of technology — the ship building practices of the Western world had conferred a major advantage on the early development of the marine steam engine.

That's because the ship that had resulted from several centuries of development had a massively complex, but extremely strong structure.¹⁸ The very sturdy skeleton was made of hundreds of pieces of interlocking timber held together by nails, screws and bolts, creating a cavernous interior covered with a thick skin of wooden planks (Fig 6.1).

頗偶然地(技術史上常有的事)西方世界造船的做法為船用蒸汽引擎的初期發展賦予了極大的優勢。

因為，經歷了好幾個世紀的發展才誕生的船有著非常複雜但極為堅固的結構。¹⁸ 它擁有由數百個互相扣連的木材構成、十分穩固的「骨架」，這些木材由各種釘子、螺絲和螺栓固定在一起，形成了一個大而深的內部空間，上面覆蓋著厚厚的木製「皮膚」(圖6.1)。

Three things followed: the first and most obvious was that there was lots of space available for the big early steam engines and boilers. Much more important though, the massive construction could easily be adapted to provide 'beds' (fixing points) for the engines and boilers (Fig. 6.1). And, most important, the complex fastening together and strength of all the parts were able to withstand the shuddering and shaking, stresses and strains of the new machinery.

Again it was in part a matter of luck, but a growing environmental crisis in the supply of timber, the increasing role of iron-made machinery in industry and an understanding of Archimedes Principle (which explains why things float) led people to think about using iron instead of wood as a material for building ships. At this point we meet the remarkable John Wilkinson again, who seems to have been responsible for the first known riveted, iron-hulled vessel to be built. It was just a barge, but Wilkinson knew he was innovating and when it was launched in 1787 he called it, appropriately, the *Trial*. It was the beginning of what would prove to be the solution to using steam power at sea since, apart from the problem of the stresses caused by engines in wooden ships, having a coal fired boiler set in a wooden ship was always risky, though accidents were actually remarkably few.

In any case, although the massive strength of the Western ship as it had developed by the early 19th century undoubtedly made the adoption of steam power easier, it was far from ideal. The strength had limits and as steam engines became larger, more powerful and more reliable — so that they were used all the time rather than some of the time — so wooden ships proved less and less capable of withstanding the

stresses. Happily, in vessels like the *Trial*, a potential substitute was already in use.

The breakthrough moment came 35 years after the *Trial's* launch. A pioneering Royal Navy officer, Captain Charles 'Mad Charlie' or 'Black Charlie' Napier RN, thought iron steam-powered vessels were the future.¹⁹ With his own money he helped design and build one at an ironworks far inland in what we would call kit form. The parts were all taken to London and assembled, and the 36.6m long, 116 ton ship, called the *Aaron Manby* after its principle designer and builder, the owner of the ironworks, was launched in May 1822. After trials, it set out from London to Paris, France, on 10th June with a full cargo and passengers, arriving after a successful voyage at an average speed of 8 knots. It stayed in service on the Rivers Seine and Loire until 1855 (Fig. 6.2).

Tucked into that story is an interesting point about technical change. The maritime community, even if open to using steam power, was extremely conservative where the design and building of ship hulls was concerned. That meant that in the first half of the 19th century, most steam engines that went to sea did so in wooden hulls because wooden hulls were what shipbuilders built. The two earliest commercial successes with steam-powered vessels, American Robert Fulton's *Clermont* of 1807, and Henry Bell's *Comet* of 1812, were both built of wood (Fig. 6.3).

In the background, however, a revolution in ship design and construction was emerging from the work of people who were not shipbuilders or naval architects, but designers and makers of new iron structures like boilers and bridges, and who were to follow up on John Wilkinson's early work. The most famous, Isambard Kingdom Brunel, was responsible for designing the *Great*

Britain, the first iron-built, steam-powered transoceanic ship that made a successful crossing of the North Atlantic Ocean in 1843. The important point is that Brunel was primarily a civil engineer, building bridges, tunnels, docks and railways.

Because it is a very Hong Kong story, we can focus on another pioneering design of the late 1830s by engineers rather than traditional shipbuilders: the first steam-powered iron warship, the *Nemesis*. The ship was part of a top secret project for the British East India Company (EIC), which was an early enthusiast for steam power at sea. The EIC planned to use radical new steamship designs as a winning weapon in its expansionist activities in Asia. But, rather than entrust the design and construction to tested British or Indian naval shipbuilders, the EIC turned to up-and-coming civil engineers, experienced in building bridges and boilers, who had attached a new shipbuilding side to an existing business.

Messrs Fairbairn & Co., originally from Manchester, had established the world's first large iron shipbuilding yard in Millwall, London, in 1835. And in Birkenhead near Liverpool, William Laird and his son John had founded their Birkenhead Iron Works in 1824. In 1839 the EIC asked the companies to design and build four iron paddle gunboats. Lairds were to build the *Phlegethon* and *Nemesis*, and the smaller *Pluto* and *Proserpine* would be built by Fairbairn.

Lairds had built their first iron vessel — a barge, like the *Trial* — in 1829, followed by a small river paddle-steamer, the *Lady Lansdowne*, in 1833. Like the *Aaron Manby*, these were prefabricated, and such river steamers had become a company speciality. That was why, when the EIC was looking for gunboats for use in Burma in the late 1830s, Lairds was chosen for the two bigger vessels.

The *Nemesis* is the one that has gone down in history — mainly by accident since she was the last to be started, but first to be successfully completed, in just three months (Fig. 6.4). After trials she set out for what proved to be China, because by the time the ship had been ordered Britain and China were at war: the First Opium War. That's how the world's first ever iron, steam-powered warship ended up in the Pearl River, where she was devastatingly successful and where, by the end of the war in 1843, she had been joined at various times by 16 other steamships. Of the total of 17, most built between 1838 and 1841, 11 were in wood and 6 in iron.

What happened in China in the First Opium War was a revelation of a new side to the power of steam at sea: making war. But the balance of wood against iron in those gunboats in China revealed that steam power had not yet become so clearly the way forward and iron hulls had not so far developed that the reigns of wood and sail were over. For that to happen the steam engine had to become more efficient, more reliable and more powerful, and iron construction had to cede to steel through improvements in metallurgy and steel plate manufacture. A key starting point in the first of those developments was improving how the vital steam was made: the boiler.²⁰

- 18 Important here too were what are called tonnage rules (how the interior volume of a ship is measured for taxation purposes). In the Western world these encouraged the development of ships with deeper interiors that, by accident, suited the accommodation of early boilers and engines.
- 19 Admiral Napier was a relative of William, Lord Napier, the British Superintendent of Trade (異目 — unfairly mistranslated as "Barbarian eye") in Guangzhou/Canton in 1834.
- 20 The Royal Navy's *Driver* (1840) and *Vixen* (1841), the Bombay Marine's *Ariadne* (1840), *Atalanta* (1836), *Auckland* (1840), *Mernnon* (1841) and *Sesostris* (1839) and the Bengal Marine's *Enterprize* (1838), *Hooghly* (1828), *Madagascar* (1838), *Queen* (1839) and *Tenasserim* (1841) were all wood. Built in iron were the Bombay Marine's *Ariadne* (1840), *Medusa* (1840), *Nemesis* (1839), *Phlegethon* (1840), *Pluto* (1839), and *Proserpine* (1840).

接下來有三個優勢。首先亦是最明顯的是，那裡有很多空間可以擺放早期大型的蒸汽引擎和鍋爐；更重要的是，巨大的結構亦易於調整，為引擎和鍋爐提供「床」（固定點）（如圖6.1）。而最重要的是船身各複雜而緊緊扣連的所有部件能夠承受得住新機械的顛簸和震蕩、壓力和拉力。

同樣，這是有運氣的成份，因木材供應而引起日益嚴重的環境危機、鐵製機械在工業世界中越發重要的角色，以及對於阿基米德浮體原理（Archimedes Principle，解釋了物體流動的因由）的理解，讓人們想出用鐵取代木作為造船的材料。就這一點，我們又回到非凡的威爾金森，他被認為建造了第一艘釘釘鐵殼船。其實那只是艘駁船，但威爾金森自知是創新的，並在1787年該船下水時，恰當地把其命名為試驗號（the *Trial*）。這就是後來被證實為船用蒸汽的解決方法的開端，因為（撇除那些因木船引擎所引發的壓力問題）把燃煤鍋爐安裝在木製船上，是非常高風險的，儘管真實發生的意外著實很少。

在任何情況下，雖然19世紀裡期發展出有著強大力量的西方船隻令蒸汽應用變得更容易，可還是遠不夠理想。船隻強度仍有限制，當蒸汽引擎變得更大型、更有效和更可靠（所以才被普遍使用），木製船隻便越來越承受不住它所帶來的壓力。幸而，在試驗號般的船隻上，已經使用上具潛力的替代品。

在試驗號啟航的35年之後，終於有了突破。一位具創見的皇家海軍軍官，被稱為「瘋狂查理」或「黑色查理」的納皮爾船長（Captain Charles 'Mad Charlie' 或 'Black Charlie' Napier RN）相信鐵製的蒸汽船就是未來的方向。¹⁹ 他自費資助位於遙遠內陸的一家冶鐵廠以組件形式設計和建造了一艘船。這些組件被運至倫敦組裝，而這艘長36.6米、116噸的船，以其設計、製造者兼冶鐵廠主人，命名為亞倫曼比號（*Aaron Manby*），於1822年5月下水。經測試後，它便於6月10日載滿了貨櫃和乘

客，由倫敦出發至法國巴黎，並以8節的平均速度成功完成行程。此後它一直於塞納河和盧瓦爾河流域服役直至1855年（圖6.2）。

隱藏在這個故事中的，是關於技術變革有趣的一節。航海社群儘管對使用蒸汽動能持開放態度，但在涉及船體的設計和建造方面極為保守。19世紀上半葉大部份用於海上的蒸汽引擎均是被配置於木製船體內，是因為造船者一直只建造木船。兩艘最早期由蒸汽推動的商用船隻——美國人富爾頓在1807年的克萊蒙特號（*Clermont*）和貝爾在1812年的彗星號——都是用木製成的（圖6.3）。

在此背景之下，船隻設計和構造的革命在後台出力的並不是造船工匠或造船工程師，而是那些追隨威爾金森早期的工作，埋首新的鐵製結構，例如鍋爐或橋樑等的設計師或工匠。當中最為人所熟知的是布魯內爾（Isambard Kingdom Brunel），他設計了在1843年成功橫越北大西洋的第一艘鐵製蒸汽越洋船大不列顛號（the *Great Britain*）。而最重要的是，布魯內爾本身是專門建造橋樑、隧道、船塢、鐵路等的土木工程師。

由於這是有關香港的故事，我們可以集中在1830年代後期，另一個來自工程師而非傳統造船者的創始設計：第一艘鐵殼蒸汽戰船復仇女神號（*Nemesis*）。這艘船是船用蒸汽動能的早期狂熱者——英國東印度公司（British East India Company，EIC）的高度機密計劃的其中一部份。東印度公司計劃在其亞洲的領土擴張活動中，利用此激進的新型蒸汽船作為致勝的殺手鐮。可是，東印度公司並未把設計和建造的任務交給已通過測試的英國或印度的海軍造船匠，而是委予有建造橋樑和鍋爐經驗、新晉的土木工程師，讓他們將新的造船業務擴展到現有業務。

來自曼徹斯特的費爾貝恩公司（Fairbairn & Co.）於1835年在倫敦米爾沃爾建立了世界上第一間大型鐵殼船廠；而萊爾德（William Laird）於1824年亦偕兒子約

翰在利物浦附近的伯肯黑德創立了伯肯黑德冶鐵廠。東印度公司於1839年委託兩間公司設計和建造了4艘鐵殼炮艇。後者造出了地獄火河號(*Phlegethon*)和復仇女神號,前者則造出較細的冥王號(*Pluto*)和女閻羅號(*Proserpine*)。

萊爾德1829年造出如駁船試驗號般的第一艘鐵殼船,隨後在1833年造了一艘小型的河用明輪汽船萊斯頓夫人號(*Lady Lansdowne*)。如亞倫曼比號般,這些都是預製的,製作這種河船已經成為該公司專長。正因如此,東印度公司在1830年代末物色用於緬甸的炮艇時,才選中萊爾德製造上述兩艘較大型的戰艦。

復仇女神號(*Nemesis*)是上述戰船中留名於歷史的那一艘——主要是因為它是第一艘遲開工卻在三個月內成功完成的(圖6.4)。經測試後,復仇女神號便被派往證實是中國的地方,因為該船被訂購之時,正值英國和中國的第一次鴉片戰爭。這就是為

何世上第一艘鐵殼蒸汽戰船出現於珠江,並於該處獲得壓倒性勝利,且在1843年戰爭結束之前,她曾經在不同的時間分別與其他16艘蒸汽船在該處共同作戰。總共17艘船中,大多製造於1838年至1841年間,11艘是木製,6艘是鐵製。²⁰

第一次鴉片戰爭期間在中國所發生的事,揭示了船用蒸汽動能的另一個方向:發動戰爭。不過,在那些用於中國的炮艇上的木材和鐵材之間的平衡,顯示出蒸汽動能當時仍然未有一個清晰的前途路向,鐵製船殼還未先進到足以推翻被木材和風帆統治的時代。要做到這一點,蒸汽引擎就必須變得更加高效、更加可靠和更加強勁,而鐵製結構則必須讓位於鋼——透過冶煉技術的改進以及鋼板生產。達到這些發展的首個關鍵出發點,是改良至關重要的蒸汽的產生方式:鍋爐。

- 18 在此,同樣重要的是被稱為噸位噸的東西(tonnage rules,一艘船的內部容量單位如何被量度以計算需要繳交的稅款,在西方世界這有助於船隻擁有更深的內艙,此深度意外地使之能夠容納早期的鍋爐與引擎。
- 19 納皮爾海軍上將是1834年在廣州(廣東)的英國駐華商務總監威廉·納皮爾勳爵(異目——被不公平地誤譯為「Barbarian eye(野蠻人的眼睛)」)的親戚。
- 20 皇家海軍的監工號(*Driver*, 1840)、狐號(*Vixen*, 1841)、阿特蘭大號(*Atalanta*, 1836)、奧克蘭號(*Auckland*, 1840)、鮑郎號(*Memnon*, 1841)、辛努塞爾特號(*Sesostris*, 1839)、孟加拉海軍的進取號(*Enterprize*, 1838)、胡格利號(*Hooghly*, 1828)、馬達加斯加號(*Madagascar*, 1838)、皇后號(*Queen*, 1839)、德蘭尚依號(*Tenasserim*, 1841)均是木製的。鐵製的則有孟買海軍的雅蘭亞典號(*Anadne*, 1840)、美杜莎號(*Medusa*, 1840)、復仇女神號(*Nemesis*, 1839)、地獄火河號(*Phlegethon*, 1840)、冥王號(*Pluto*, 1839)和女閻羅號(*Proserpine*, 1840)。

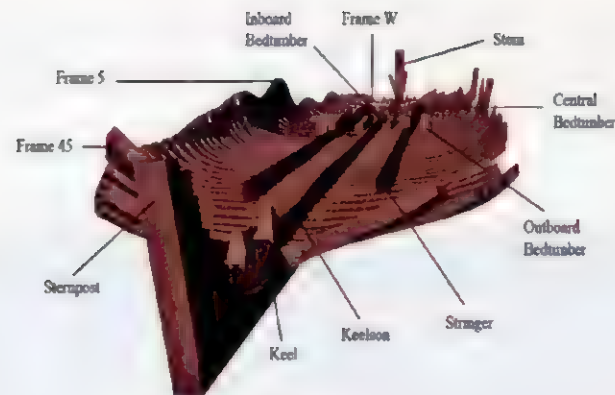


Figure 6.1: The massive, complex structure of the early American steamboat *Phoenix* that caught fire and sank in 1819. Note the 'bedtimbers' added to support the engine.

(Source: George Schwarz, "Archeology of the early American steamboat *Phoenix*", *The International Journal of Nautical Archaeology* (2016) 45.1: 119-140)

圖6.1: 美國早期蒸汽船鳳凰號巨大而複雜的結構,此船因起火於1819年沉。注意它為了支撐引擎而增加了「枕木」。

(資料來源:喬治·史瓦茲(George Schwarz),「美國早期蒸汽船鳳凰號的考古學」,《國際航海考古學雜誌》,2016年,45.1: 119-140。)



Figure 6.2: The *Aaron Manby*. (the caption reads, "Iron steamship (operating) between Paris and Le Havre, by a patent for (its) invention, importation and improvement".)

(Source: Wikipedia, public domain)

圖6.2: 亞倫曼比號。(標題為「在巴黎和勒阿弗爾之間的鐵製蒸汽船(正在運行)擁有(其)發明、進口和改良的專利權。」)

(資料來源:維基百科。)



Figure 6.3: Henry Bell's *Comet* off Dumbarton, 1812.

(Source: Bennet Woodcroft, *A sketch of the origin and progress of steam navigation from authentic documents*, London: Taylor, Walton and Maberly, 1848.)

圖 6.3：貝爾的彗星號離登巴頓，1812。

（資料來源：班內·伍德克羅夫特（Bennet Woodcroft），「來自真實文獻的蒸汽航海之起源與發展速記」（A sketch of the origin and progress of steam navigation from authentic documents）倫敦：Taylor, Walton, and Maberly，1848。）



Figure 6.4: The HEIC *Nemesis* in Chinese waters.

(Source: <http://collections.rmg.co.uk/collections/objects/110858.html>, London: Henry Colburn, 1844, engraved S. Bull.)

圖 6.4 在中國水域中的復仇女神號。

資料來源：<http://collections.rmg.co.uk/collections/objects/110858.html>
倫敦：亨利·科爾本（Henry Colburn），1844年，刻有S Bull。）

INCREASING THE PRESSURE

All early steam engines worked with steam at very low pressures of under seven pounds per square inch (0.048 MPa). The main power came from the pressure difference between the steam and the vacuum created by the condensing steam in the condenser. The reason is simple. In general, the quality of engineering and the design of early boilers were not suitable for higher pressures. With higher pressures too much steam was lost through leaks and, worse, boilers often exploded killing and maiming anyone close by, as well as damaging or even destroying what enclosed them, whether a building or a ship.

所有早期的蒸汽引擎都以大約每平方吋7磅(0.048 帕斯卡)的低壓蒸汽推動。主要動能生產自冷凝器冷凝水蒸汽時，蒸汽與真空之間的壓力差。原理很簡單。一般來說，高壓並不適用於早期鍋爐的工程性質和設計，愈高的壓力就會讓愈多蒸汽因為洩漏而流失，更糟糕的是鍋爐經常爆炸導致附近的人傷亡，甚至摧毀附近的物件，包括建築物或船隻。

In the first decade of the 19th century, with the work of Richard Trevithick in Britain and American Oliver Evans, things began to change. Both engineers had understood two things: one was that working at higher pressures made a steam engine far more efficient. The other, which was critical to steam being successfully used to power ships and the railway trains, was that a high pressure engine of the same horsepower as a low pressure engine would be much, much smaller.

To understand where these ideas came from, we need to track right back to the beginning of the story of steam and to the new thinking about gas and pressure that took place at the same time.

Key figures are two people who were working on pretty much the same idea at more or less the same time, a feature of almost every aspect of the story of steam. These were the British thinkers Robert Boyle and Henry Power who, as a result of experiments in 1660–62, independently came up with a law linking the pressure of a gas with its volume (Fig. 7.1). This is usually expressed as: $P_1V_1 = P_2V_2$

In words, that says that the product of the pressure of a gas and the volume it occupies is constant, so that if the pressure increases, the volume proportionately decreases and vice versa. That law, however, only applies when the temperature of the gas remains constant. And that brings us to a third important figure, Frenchman Edme Mariotte, who in 1675 realised the importance of keeping temperature constant, which is why today we write of the Boyle-Mariotte Law.

It took nearly two more centuries before all the implications of this were worked out, more laws had been derived by experiment and the kinetic theory of

gases had emerged. We don't need to go into the very complex detail, except maybe to note how critical the realisation was that, depending on temperature and pressure, all matter can exist in any of three states: solid, liquid and gas, that steam is just a gas and that energy must either be added or given off as the matter changes — technically goes through a phase change — from one state to another.

What matters is that coming to the sophisticated understanding of how gases behave under varying pressures and temperatures was critical to the development of the increasingly efficient and powerful steam engines without which the maritime transport revolution of the 19th century could never have happened. We'll come back to the engines that the high pressure steam was to drive in Chapter 10. In the meantime, we can briefly focus on what made the steam in the first place: the boiler, an often overlooked but vital first component in the steam revolution.

We've noted that the first boilers were just like kettles or pans with lids with a pipe leading out of the top to take the steam to the engine. They were even called kettle boilers. By the end of our story, the boilers in ships were massively complicated water tube boilers. You can compare figures 7.2 and 7.3 to see the difference.

Newcomen's kettle boiler was dealing with steam at less than three pounds per square inch (0.2 MPa) and a steam temperature at or close to water's boiling point of 100°C. The Admiralty 3-Drum, when first introduced in the mid-1920s, was operating at 300 psi (2.0 MPa) with steam at 316°C. The story that took the world of marine steam from Newcomen's kettle to the high-performance boilers of the 20th century is complex and involved a bewildering

variety of more or less successful boilers invented by numerous people for lots of different purposes from driving mill machinery to railway engines to ships. A look at the Wikipedia List of Boiler Types by manufacturer with its 129 entries is very instructive!²¹

We can focus on just three much simpler issues. Where did the feed water come from — that's the water the boiler boiled to make the steam. What fuel was the source of the heat that boiled the water? How did the heat of the boiler get transferred to the water to boil it? That's because solutions to those three issues are really what lie at the heart of improving the design of ships' boilers, and so of creating the steam supply that ships' engines needed. We need to remember, however, that as we look at these developments they should not be seen in isolation. The development of marine steam engines and of their boilers went hand-in-hand, advances in one calling for improvements in the other.

There isn't really a correct order in which to deal with the four topics. As with every other aspect of the steam revolution, how each worked out was closely entwined with developments in the others. But the water that created the steam is a good place to start because it was one of the biggest problems the steam engine faced when it went to sea.

Fresh water on a ship has always been scarce, and special arrangements have always been needed to make sure there was enough for everyone on board for as long as a voyage lasted. Pictures of Chinese junks, for example, show special water containers the size of large baths fixed to the ship's side (Fig. 7.4). But the human crew needed fresh water. So, when the steam engine came along, engineers' eyes turned to a much more

readily available source of water, the sea. After all, they reasoned, when you boil seawater it makes steam, and exactly the same sort of steam you get from boiling fresh water.

It seemed an excellent way to solve the problem since the sea would never run dry. The saltwater would happily boil and provide the steam needed. The problem was that the saltier water gets as a result of being boiled and the steam evaporating, the more heat has to be generated to keep it boiling and the temperature of the solution creeps up to the point, at around 107.8°C, when the boiling liquid — the brine — becomes saturated and salt starts to be rapidly deposited in the boiler. Trial and error indicated that things remained controllable provided the water in the boiler stayed below 13% salt — compared to seawater's natural condition of 3.3% salt.

To get to that point, however, was a steep learning curve. Hot saltwater is very corrosive, and designing boilers that could stay water- and steam-tight as well as handle even quite modest steam pressures of under 30 psi (206.8 kPa) was a challenge. The other problem was that although at low pressures salt deposit on the boiler walls wasn't a problem, another component of seawater, calcium sulphate, was. Its deposits got worse as feedwater density, temperature and pressure increased. The deposit was called 'scale', and hugely reduced the efficiency of heat transfer as well as raising boiler pressures dangerously. That meant boilers had to be regularly shut down and physically descaled (Fig. 7.5).

We needn't go into detail, but the solutions that had emerged by around 1870 meant stopping using seawater and using a closed freshwater system that only needed topping up now and

then. Key technical developments included the evaporator, a separate bit of machinery which used boiler steam to turn seawater into fresh water so fresh water was available to top up the feedwater. The closed feedwater system itself was given a surface condenser, which used seawater to condense the steam exhausted from the engines, and a feedwater pump to ensure water circulation in the closed system. The end result was much less prone to corrosion and leaks. Better, the life expectancy of a marine boiler — as little as two to three years for the first examples in the 1840s–1860s — had increased to nearly 20 years by the 1900s.

Whilst both wood and coal fuelled early boilers, it was very soon realised that all boiler fuel was not equivalent. Coal was evidently superior to wood, and some coal was more equal than other coal. What's called the thermal efficiency of a fuel — basically how much water was turned into steam by burning a set quantity — came to matter greatly. From the mid-19th century onwards, naval authorities and shipping companies monitored coal consumption and carried out trials to decide which coal was best. The basic ranking was simple: the nearest a coal was to pure carbon, the better it was. What became known as 'steam coal' or 'bituminous coal' was what ships sought. Although it was the most expensive, anthracite — a very dense coal — was the best, and Welsh anthracite was thought to be the best of all (Fig. 7.6).

Other than thermal efficiency, there were two other reasons for the choice of coal. Lower quality coal left more residue — known as ash and clinker — which constantly had to be removed from the furnace and, when it had cooled, thrown overboard.²² As important, lower quality coal took up more storage space —

known as bunker space — than higher quality coal, so the ship ran out of coal more quickly and the expensive, time-consuming and filthy job of coaling ship had to be done more often. Of course, during the heyday of steam, most of the hard work of coaling was not done by Western ships' crews, but by contracted local labour — in Japan by the famous Nagasaki teams with many women (Fig. 7.7 & 7.8)!

The world's oceans were transformed because of the importance of coal, with specialist coaling station ports being developed for naval and commercial use both in out of the way places like the Cape Verde Islands and in extensive coaling facilities essential to any major port. By 1892, for example, Hong Kong was importing 70,000 tonnes of coal a year from Wales, Japan and Australia, and Singapore imported up to 100,000 tonnes. By 1909 that had risen to 90,000 tonnes in Hong Kong and about 115,000 in Singapore. Just before the Japanese invasion in 1941, Hong Kong's annual imports of coal averaged 100,000 tonnes.

Then, by the end of the 19th century and after the discovery of the industrial uses of oil, the first experiments were taking place in replacing coal with oil. Once the technical problems of designing burners had been surmounted, oil proved far more thermally efficient. Already by 1909, Hong Kong was listed as having in stock 3,000 tonnes of fuel oil for shipping. By the end of the First World War, most of the world's navies were completing changing to oil-fired boilers, although coal remained an important fuel through until the 1960s. In 1967 the port of Hong Kong still maintained a stock of 1,000 tonnes of coal to provide fuel for ships that still used it, in contrast to over 300,000 tonnes of boiler furnace fuel oil.

Solving the problem of getting the heat from the coal, and later oil, to the feedwater was a constant exercise in ingenuity, as we have seen with the 129 different boiler types. It was obvious that the more surface area of heat the boiler feedwater was exposed to, the more efficient the boiler would be. The puzzle was how to increase the surface area beyond the base of the simple kettle.

The first answer was the box boiler, basically a big, water-filled box divided into narrow vertical sections, which sat above the boiler furnace so that the heated air was in contact with the sides of the water-filled sections. Like almost all early boiler designs, these couldn't handle pressures much over 20 psi (137.9 kPa), because neither the design nor early iron sheet and riveting technologies were up to the job.

However, ever since the 18th century two other ideas had been in existence, though getting them to work required better engineering skills and metallurgical knowledge than were available. The first was pushed forward primarily by the development of steam-powered land vehicles, or railway engines. It was what was called the fire tube boiler. The simple idea was to make all the hot furnace gases pass through a network of tubes built into the boiler — a principle rather like the element of an old-fashioned electric kettle.

By the 1840s the first fire tube boilers were appearing in ships, developing steadily to offer pressures up to 30–35 psi (206.8–241.3 kPa) by the 1860s. And then in 1862 the old box shape of the fire tube boilers was replaced by a cylindrical shape able to cope with much higher steam pressures. The 'Scotch (Fire Tube) Boiler', as it was labelled, stayed in use in merchant shipping into the 20th century and developed sufficiently to offer steam

pressures up to 215psi (1480 kPa) (Fig. 7.9).

But for the even higher pressures and absolutely dry super-heated steam that would be needed when a new form of steam engine — the steam turbine — made its appearance in the 1890s, a more efficient solution was needed. This was the water tube boiler. The easy way to understand this is to turn the fire tube boiler inside out, as it were, so that instead of hot gas passing through tubes in a vessel full of water, tubes full of water pass through a furnace full of hot gas (Fig. 7.10). As Figure 7.3 shows, actual advanced water tube boilers were hugely complicated, but Figure 7.9 sets out the basics.

After the water tube boiler, the only major change was the switch to steam generated by nuclear reactors, a more thermally efficient system. The boiler was exchanged for a steam generator, which is a sort of heat exchanger between the hot liquid or gas output of the nuclear reactor and the closed feedwater system driving the steam turbines (Fig 7.11).

However, because nuclear power is expensive and requires very high standards of training and maintenance, it has only really been of interest to the navies of the world's major powers. That said, an experimental nuclear steamship, the *NS Savannah*, echoing the first *Savannah* of 1819, was completed in 1962. She was never a commercial success and had never been intended to be, but before she was taken out of service in 1972, she had visited Hong Kong four times (Fig. 7.12).²³

- 22 Marine archaeologists are now beginning to use heaps of clinker to track steam ship routes – see <https://www.hakaimagazine.com/news/trail-rocks-traces-historical-steamship-routes/>.
- 23 In 2019, after 47 years out of service including 13 as an unsuccessful museum ship (1983–1994), she was being decommissioned and her reactor is being removed. She is registered in the USA as a National Historic Landmark, so the hope is that post-decommissioning, which must be completed by 2031, the ship will find a home where she can be visited

在1910年代，在英國的特里維西克(Richard Trevithick)和美國人埃文斯(Oliver Evans)的努力下，事情開始有轉機。上述兩位工程師都理解兩件事，首先是高壓可以令蒸汽引擎更高效；其次是同等馬力的高壓引擎比低壓引擎體積細小得多，這亦是蒸汽被成功地應用於船隻和鐵路的關鍵。

要了解這些意念是怎樣來的，我們便要回顧蒸汽故事的起源，以及當時有關氣體和壓力的新想法。

關鍵人物是兩位在差不多時間不約而同地推出幾乎一模一樣的理念的人——波爾耳(Robert Boyle)和波沃爾(Henry Power)。他們分別在1660至1662年，各自透過實驗得出氣體壓力與其體積之間關連的定律(圖7.1)。此定律通常以「 $P_1V_1 = P_2V_2$ 」表達。

簡而言之就是說，氣體壓力與其所佔體積的乘積是恆定的，因此，若壓力增大，則其體積成比例地變小，反之亦然。可是，此定律只適用於氣體在恆定溫度的情況下。然後，第三個重要的人物出現了——法國人馬略特(Edme Mariotte)在1675年意識到保持溫度不變的重要性，這便是我們今天把此定律命名為「波爾耳·馬略特定律(Boyle-Mariotte Law)」的原因。

花了將近兩世紀，人們才算出所有這些結果，透過實驗得出更多定律，並形成分子運動論(Kinetic theory of gases)。我們毋須進入那些極為複雜的細節，也許只需要知道，因應溫度和壓力，所有物質都能以三種狀態存在：固態、液態、氣態。而蒸汽只是一種氣體，當轉換任何另一種形態時(技術上的相態轉變)，其能量定會有所注入或釋放。

重要的是，精密地理解氣體在不同壓力和溫度下的表現，對於發展蒸汽引擎的效能和力量是十分關鍵的。而如果没有這些蒸汽引擎，19世紀的海上交通革命便不可能發生。在第十章中，我們將回到高壓蒸汽驅動的引擎。我們可以先集中在產生蒸汽的第

一個步驟：鍋爐——一個經常被忽略卻是蒸汽革命中至關重要的首個元素。

我們已經知道第一個鍋爐就像水煲或像平底鍋，頂部連著蓋和管道把蒸汽導進引擎裡。它們甚至被稱為「水煲鍋爐(kettle boiler)」。在蒸汽故事的尾聲，船用鍋爐已發展成極為複雜的水管鍋爐。你大可比較一下圖7.2和7.3之間的差別。

紐卡門的水煲式鍋爐是以少於每平方吋3磅(0.2帕斯卡)的壓力處理蒸汽，在這壓力下蒸汽溫度是同時在或接近水的沸點即攝氏100度。而英國海軍部三筒式水管鍋爐1920年代首度面世時，便以每平方吋300磅(2.0帕斯卡)於攝氏316度運作。把船用蒸汽世界由紐卡門的「水煲」帶到20世紀高效能的鍋爐是一個極為複雜的過程，且涉及一系列因緣際會，由很多人因著不同目的(由驅動製造廠的機器到鐵路引擎以至船隻等)而設計出或多或少地成功的鍋爐。看看維基百科上就生產者順序列出的鍋爐款式，共有129項則可見一斑！²¹

我們可以細看有關鍋爐其中較簡單的問題：那些用來煮沸以產生蒸汽的水從何而來？煮沸水時所用的燃料來源是什麼？鍋爐的熱如何傳遞到水以將之煮沸？因為針對這三個問題的解決方案實際上是改善船用鍋爐設計，並因此創造船用引擎所需蒸汽供應的核心。不過，當我們檢視這些發展時，我們要記住不能單獨地看待它們。船用蒸汽引擎與其鍋爐兩者的發展關係密切，一方面的進展往往會啟發另一方面的改良。

處理這些問題其實並沒有真正正確的次序，因為蒸汽革命的一個局面的如何發展總是緊密地關係著另一些方面的進展。可是用以製造蒸汽的水是一個頗不錯的開始，因為這是當蒸汽引擎被使用於船上時其中一個最大的問題。

船上總是缺乏新鮮食水，且需要特別的安排以確保船上所有人在旅途中都有足夠的食水可用。比方說，中國帆船的圖片中可見特製的、大小與大型浴缸相若的盛水器被固定在船側(圖7.4)。但船員需要新鮮食

水，因此要為蒸汽引擎找水源的話，工程師的目光更多是放在比較現成的水源——海洋。畢竟他們推論燒海水所取得的蒸汽，與燒淡水所取得的蒸汽完全一樣。

這似乎是解決問題的極佳辦法，因為海洋永遠不會乾涸。但問題在於，鹹水越是被煮沸並蒸發成蒸汽，它就會變得越鹹，讀其保持沸騰所需的熱量便越多，溶液的溫度會慢慢升至大約攝氏107.8度——當沸騰的液體（濃鹽水）變得飽和，鹽便開始迅速沉澱於鍋爐。反複的嘗試證實，若鍋爐中的水鹹度維持13%以下，那麼一切都在控制範圍之內——相對於天然海水的鹹度為3.3%。

然而，要達到這一點需經過很艱難的學習過程。熱的鹽水具很強腐蝕性，因此要設計一種既能保持水密和蒸汽密封又能處理低於每平方英寸30磅（206.8帕斯卡）蒸汽壓力的鍋爐也是種挑戰。另一個問題是，儘管在低壓環境下鹽沉澱於鍋爐壁並不成問題，但海水的另一個成份硫酸鈣的沉澱卻會導致更差的狀況——供水的濃度、溫度、壓力均會上升。該沉積物被稱為「水垢」，極大地降低了傳熱效率，並提高了鍋爐壓力導致危險。這意味著鍋爐必須定期關閉並「除垢」（■7.5）。

解決的辦法在1870年左右面世，方法是停止使用海水而改為使用一個封閉的、只需不時把它加滿的淡水系統。關鍵的技術發展包括蒸發器——是一台獨立的機器，它利用鍋爐產生的蒸汽把海水變成補給供水用的淡水。上述的封閉式供水系統本身附有一個表面冷凝器，以利用海水冷凝引擎所排放出的蒸汽，並設有一個供水泵以確保封閉系統中的水循環運行。最終結果是大大減低了腐蝕和洩漏。船用鍋爐的預期壽命已經由1840年代至1860年代首批的2至3年，增加到1900年代的接近20年。

儘管木材和煤炭都為早期鍋爐提供了燃料，但很快人們意識到所有鍋爐燃料都不相等。煤顯然勝過木，有些煤則比其他煤更平等。煤的熱效率（thermal efficiency）非常重要，基本上就是指通過燃燒一定份量

的煤，讓多少份量的水變成蒸汽。自19世紀中開始，海軍專家和造船公司均監控著煤的消耗情況，並進行試驗以決定哪種煤最好。基本的評定十分簡單，越接近純碳的煤越好。日後所謂的「蒸煤」或「煙煤」都適合船用。不過無煙煤（一種非常高密度的煤）卻是最好的——儘管最昂貴，而當中要數威爾士的無煙煤為最佳（■7.6）。

除了熱效率之外，選擇煤時還應考慮兩點。質量較差的煤會留下更多的殘餘物（即是煤灰和煤渣），必須不斷從爐中清理掉，並待其降溫後丟出船外。²²重要的是，較低質的煤相對於較高質的煤佔用較多的儲存空間（即煤倉），因此船隻會耗煤較快、成本更高，費時且艱難的加煤工作不得不更頻繁地進行。當然，在蒸汽的鼎盛時期，加煤的艱苦工作大部份都不是由西方船員完成，而是由當地的勞工承包——若是在日本，就是著名的長崎團隊，當中許多勞工都是婦女（■7.7 & 7.8）！

由於煤炭的重要性，世界海洋發生了變化，在維德角群島等偏遠地區以及任何主要港口必不可少的廣泛的煤炭設施中，都開發了專門的「加煤站」港口供海軍和商業用途。香港在1892年就從威爾士、日本、澳洲等地每年進口7萬噸煤，新加坡更進口多達10萬噸；到1909年，香港增至9萬噸而新加坡已達11.5萬噸。在1941年日本入侵之前，香港每年的煤進口量平均為10萬噸。

在石油的工業用途被發現後的19世紀末，有人進行了首個以石油取代煤的實驗。設計燃燒器的技術問題解決，石油被證實具有更高的熱效率。1909年，香港已被列為擁有3,000噸可運輸燃油的庫存。儘管煤在1960年代之前依然是十分重要的燃料，但第一次世界大戰結束前，全球大部份海軍都陸續完成燃油鍋爐的更換。相對於當時超過30萬噸的鍋爐用燃油，香港的港口在1967年依然維持1,000噸煤的庫存，為仍使用煤的船隻供應燃料。

要解決從煤或其後的石油取得熱能，引伸至給水的問題，是一場持續不斷的創造

力訓練——就如我們已經看過的129種不同種類的鍋爐。明顯地，若是鍋爐讓水曝露於熱量表面積越大，鍋爐的效率就越高；難題就在於如何增加該表面積，使其超越普通「水煲」的底部。

第一個方案是「箱型鍋爐」——基本上就是一個裝滿水的大箱子，裡面分成狹窄的垂直部分，該箱子位於火爐的上方，以便已被加熱的空氣充份接觸到箱裡盛滿水的一面。由於設計上的限制，以及早期的鐵皮和鉚接技術都力有不逮，這些鍋爐（與幾乎所有早期鍋爐一樣）不能承受超過每平方吋20磅（137.9帕斯卡）的壓力。

18世紀以後，有另外兩種方案出現，儘管實踐起來需要比初期的更精進的工程技術和冶鍊知識。最早成功的產品是被蒸汽動能汽車或鐵路引擎的發展所推動，被稱為火管鍋爐。是令所有熱爐氣體穿過鍋爐內置的管道網絡的簡單想法——原理類近於舊式電熱水煲。

1840年代，首台火管鍋爐出現於船上並穩定發展，直至1860年代已經供應高至每平方吋30-35磅（206.8-241.3帕斯卡）的壓力。然後到了1862年舊款火管鍋爐的「箱」型設計被認為可以應付更高蒸汽壓力的圓柱型所取代。被稱為蘇格蘭（火管）鍋爐的產品，在20世紀一直被商用船隻採用，並且發展到足以提供高達每平方吋215磅（1480帕斯卡）的蒸汽壓力（■7.9）。

不過，在約1890年代出現了較新型的蒸汽引擎（蒸汽渦輪機），要滿足更高壓、絕對乾燥、過熱蒸汽的需求，就需要更有效的解決辦法：這便是水管鍋爐。簡單來說，可以理解為火管鍋爐的相反原理——不是讓熱氣穿過裝滿水的容器中的管道，而是讓水流過充滿熱氣的火爐裡的管道（■7.10）。就如圖7.3所顯示，真實的高階水管鍋爐構造非常複雜，而圖7.9則顯示了基本型。

繼水管鍋爐之後，唯一的大轉變就是改為使用核反應堆產生蒸汽，這是熱效率較大的系統。將鍋爐換成蒸汽生成器，該蒸汽生成器是核反應堆的熱液體或氣體輸出與驅

動蒸汽輪機的封閉給水系統之間的一種熱交換器（■7.11）。

然而，由於核能是非常昂貴且需要很高標準的訓練和保養，因此只有世界大國的海軍有條件使用。實驗性的核動力蒸汽船薩凡納號（NS Savannah，遙遙呼應1819年的第一艘薩凡納號）於1962年完成。此船從不打算、亦沒有取得商業上的成功，但它在1972年服役後，曾經到訪過香港4次（■7.12）。²³

21 詳見 https://en.wikipedia.org/wiki/List_of_boiler_types_by_manufacturer/。

22 海洋考古學家現在開始使用煤渣堆來追蹤蒸汽船的航行路線，見：<https://www.hakaimagazine.com/news/trail-rocks-traces-historical-steamship-routes/>。

23 在2019年，已經服役47年，包括13年作為失敗的博物館船（1983-1994年），該船已經退役且其反應堆已被移除。她已在美國註冊為國家歷史地標，因此希望退役後（必須在2031年之前完成），可以到安置的地方並開放參觀。

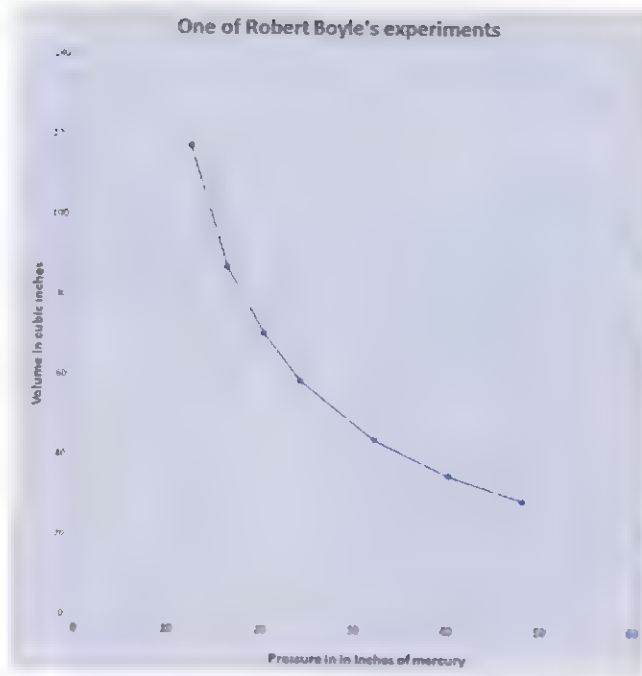


Figure 7.1: A graph of the relationship between the pressure and volume of a gas from Boyle's original data. (Source: SNGD.)

圖 7.1：波爾耳關於氣體壓力與容積關係圖表的原始數據。(資料來源：SNGD。)

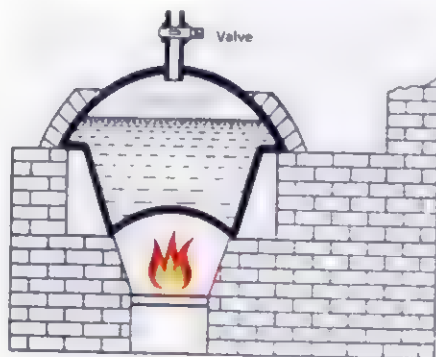


Figure 7.2: A cross-section of the 'kettle' boiler of Newcomen's engine. (Source: Illustrated by Stephen Davies.)

圖 7.2：紐卡門引擎中「水煲」鍋爐的切面圖。
(資料來源：由史提芬·戴維斯繪圖。)

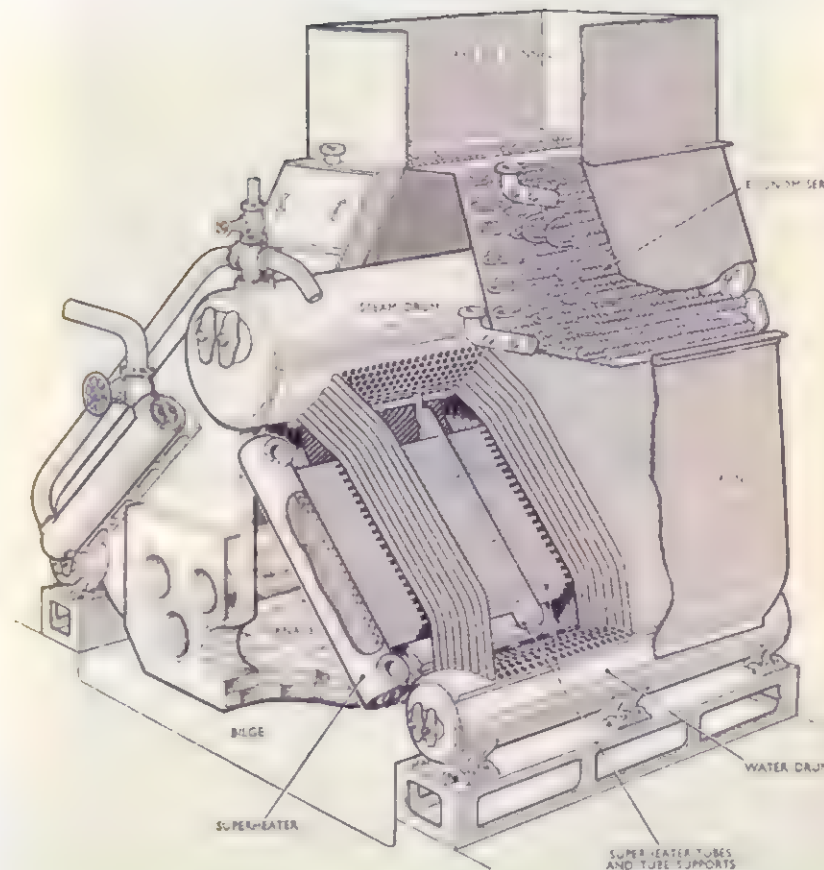


Figure 7.3: A 3D cutaway view of an Admiralty 3-Drum water tube boiler of the 1920s.

(Source: UK National Gas Turbine Research Establishment, Farnborough at <http://www.ngte.co.uk/buildings/bth/bel.htm>.)

圖 7.3：1920 年代英國海軍部三筒式水管鍋爐的 3D 剖視圖。
(資料來源：英國國家燃氣輪研究機構，法恩伯勒。
網址為 <http://www.ngte.co.uk/buildings/bth/bel.htm>。)



Figure 7.4: A sailing junk's freshwater tank.
(Source: Hong Kong Maritime Museum with edit by SNGD.)

圖 7.4：一艘帆船的淡水箱
(資料來源：香港海事博物館 由SNGD編輯。)



Figure 7.5: How bad scale build-up in a boiler water tube can be!
(Source: Wikipedia https://en.wikipedia.org/wiki/Boiler_feedwater/.)

圖 7.5：鍋爐水管積垢的情況惡劣到這個程度！
(資料來源：維基百科 https://en.wikipedia.org/wiki/Boiler_feedwater/。)

Coal type	% of Carbon	% of moisture	Heat Content (MJ/kg)
Anthracite	86-92	7-10	32-33
Bituminous coal	76-86	8-18	25-33
Lignite			

Figure 7.6: The classes of coal — only desperate ships used any of the bottom three classes.
(Source: Created by Stephen Davies.)

圖 7.6：煤的等級——只有極為情急的船才會使用下面三種等級的煤
(資料來源：由史提芬·戴維斯繪製。)



Coal-shipping, Nagasaki.

長崎・長崎炭石船積み場

Figure 7.7: Women and men coaling a ship in Nagasaki (c.1910).
(Source: <https://www.oldtokyo.com/ship-coaling-nagasaki-c-1910/>)

圖 7.7：在長崎，男男女女成群結隊地為一艘船加煤（約1910年）。
(資料來源：<https://www.oldtokyo.com/ship-coaling-nagasaki-c-1910/>。)



Figure 7.8: Coolies coaling ship in Hong Kong in the 1920s.
(Source: Courtesy IDJ at <https://industrialhistoryhk.org/coal-hong-kong/>.)

圖 7.8：1920年代，香港的苦力為船加煤。
(資料來源：IDJ提供。<https://industrialhistoryhk.org/coal-hong-kong/>。)

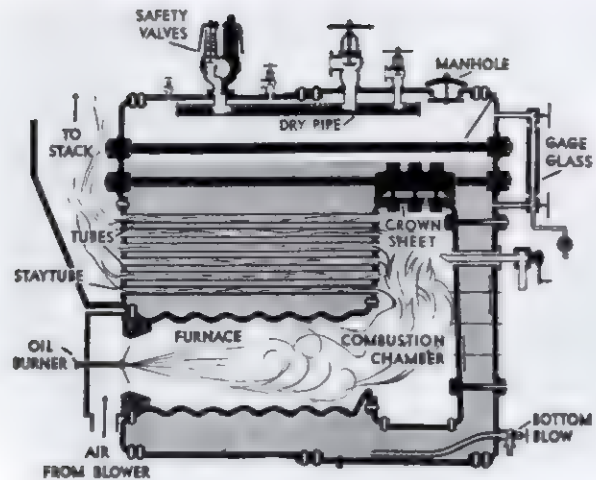


Figure 7.9: Side view of a Scotch fire tube boiler — hot gas passes through tubes in the water-filled boiler.
(Source: <https://maritime.org/doc/merchant/engineering/part2.htm#pg22/>.)

圖 7.9 蘇格蘭火管鍋爐的側視圖——熱氣穿過注水鍋爐中的管子。
(資料來源: <https://maritime.org/doc/merchant/engineering/part2.htm#pg22/>.)

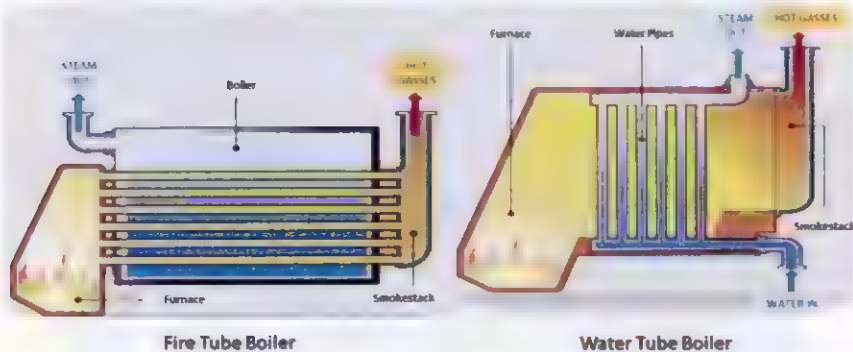


Figure 7.10: Basic schematic of fire tube and water tube boilers.
(Source: SNGD.)

圖 7.10：管和水管鍋爐的基本圖解。
(資料來源: SNGD.)

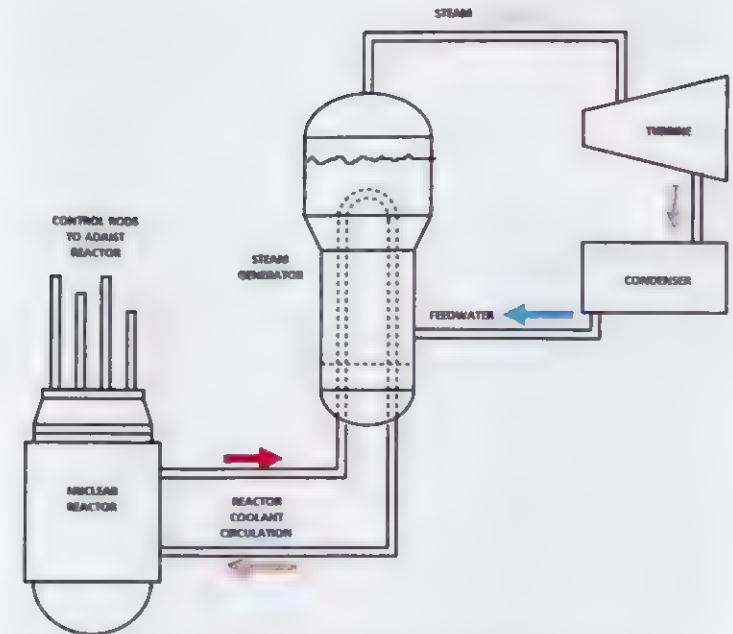


Figure 7.11: A simple nuclear reactor steam turbine configuration.
(Source: SNGD.)

圖 7.11：簡單的核反應堆蒸汽輪機配置。
(資料來源: SNGD.)



Figure 7.12: The NS Savannah on her third visit to Hong Kong
(Source: South China Morning Post, 8.6.1970, p.6.)

圖 7.12：薩凡納在她第 3 次訪問香港時。
(《南華早報》1970 年 6 月 8 日 第 6 頁。)

8

ART MATTERED

藝術的重要地位

Throughout this book so far, we have been looking at illustrations to help us understand the developments being described. As we saw in Chapter 4, drawing techniques, developing from upheavals in art that had started in Europe in the 15th century, were critical to providing engineers with a key tool for improved design and production. But we have also seen — perhaps without realising it — that art in a more traditional sense also played a significant and often overlooked role in the story of steam.

到目前為止，綜觀此書，我們看到很多幫助了解上述發展的插圖。我們在第4章裡看到，15世紀歐洲藝術革新的繪畫技巧是工程師改良設計和產品的關鍵工具。不過，我們亦看到（或者看不到），傳統意義下的藝術於蒸汽故事裡其實扮演著十分重要卻經常被忽視的角色。

How?

Any major technological change flourishes only if it finds acceptability both with decision makers and the general public. Consider the recent fate of nuclear power generation for electricity on the one hand and the success of the motor car on the other. It is obvious when you think about it, but any major innovation is necessarily disruptive, often threatening and, in being entirely new, subject to the misunderstandings of ignorance. Everything people are used to doing and seeing is either explicitly or implicitly being called into question. Many people in 1830's Europe, when told that the new railway trains could carry people at 30 miles per hour (48 kmh), thought that at such speeds they would be unable to breathe. So a key issue becomes how any novelty is treated by those who play key roles in forming elite and public opinion. And helping from such opinions is basically what the various branches of creative activity such as painting, architecture, sculpture, literature, music and theatre do.

The world of artists — generously understood as all the contributors to a society's cultural life — is usually considered as standing in opposition to science, engineering, technology and maths. Up to a point that has quite often been the case, but as we can see in the many illustrations in this volume, art was often hard at work in the service of steam. Artists, after all, often think of themselves as radical visionaries.

How the visual arts, for example, might be thought to serve the emerging world of steam power is clear where it is a question of mechanical drawing and its role in precision engineering. It is equally obvious in Europe's rapidly expanding 18th and 19th century worlds of commercial print-making, both in the images that

were sold to an increasingly affluent middle class to help decorate their homes — like the print of HMS *Rattler* towing HMS *Alecto*. Illustrations like the print of HEIC *Nemesis* accompanying the books and news stories that informed people about the new world that was emerging — and, like the advertisement for the *Aaron Manby*, about the growing world of commercial advertising. Indeed after 1843, with American Richard M. Hoe's invention of the steam-powered rotary printing press, even mass-produced images relied increasingly on steam to be printed and, via the steam-powered railway train, to be distributed.

In the story of the rise of steam power, what is sometimes called 'high art' was also as often supportive of the weird and wonderful new machinery and its transformative potential as it was hostile. Mary Shelley, the author of the usually misunderstood early 19th-century novel *Frankenstein; or, The Modern Prometheus*, was married to Romantic poet Percy Bysshe Shelley. In both their cases science and technology were more heroes, if flawed heroes, than villains. Percy Shelley, for example, was a great enthusiast for steam, and in Italy where he was to die in a boating accident in 1822, he gave financial help to his friend Henry Willey Reveley, who was trying to design and have built a steam boat to work commercially between Marseille in France and Livorno in Italy.

That attitude, in which steam is celebrated rather than condemned, is perhaps best known in the visual arts in the work of J.M.W. Turner, whose *Snow-Storm - Steam-Boat off a Harbour's Mouth* (1842) places the new technology central to a visually stunning work of art (Fig. 8.1).

We can stay momentarily with Turner, because another of his paintings introduces us to two things: one is the

role of marine art in making steam power not just familiar and acceptable, but something to celebrate and take pride in even as we may regret the passing of the world being replaced. The other is how that role was played out in our own China coast world in the work of those known as the China Coast or China Export artists.

An earlier painting by Turner shows perfectly how art illustrated the transformative quality of marine steam power at the same time as linking it to the maritime world it was replacing. In *The Fighting Temeraire, tugged to her last berth to be broken up, 1838* (Fig. 8.2), Turner again gives the new world of marine steam centre place. But he does so by showing steam in a humdrum, workaday and very minor role — that of a tug — against the backdrop of what, to the people who would have seen his painting in mid-19th century Britain, was a direct reference to Britain's rise to global maritime dominance through the fighting qualities of its Royal Navy's late 18th and early 19th century wooden sailing warships.

The key point to notice is that Turner is showing us a very calm sea — a sea with no wind. Bustling along, entirely unaffected by the absence of wind and, as we can see from its funnel smoke, creating its own, is a steam paddle tug towing to its demise the once mighty ship of the line, the remaining few of its now useless sails all furled. Off to the right in the middle distance, another steam paddle tug trailing its funnel smoke is towing a ship with all its sails stowed up river. Close to the right of the *Temeraire* and its tug are two sailing craft — a working barge with just its mizzen sail hanging baggily drifting out on the tide and, far beyond it, a square-rigged ship leaving the river, ghosting along with all sails set but almost

becalmed. Steam is the future, black and a bit ugly though it may appear to be. Sail is drifting away into the past... or is being towed to its final resting place.

That's the take of an artist of surpassing genius. Many more workaday artists, trying to make a living by pleasing a clientele, had an altogether more single-focused view. What the ships' captains and owners who had commissioned the paintings wanted was what the artists provided and, if the subject was a steamship as it was increasingly as the 19th century wore on, then the ship would be shown in all its pomp.

In Hong Kong, from the 1855 painting of one of the earliest locally owned steamships, the small paddle steamer *Spark* (Fig. 8.3), operated as a ferry between Hong Kong and Canton (Guangzhou) by the American James Bridges Endicott, through to the c.1949, Jardine Matheson, Indo-China Steam Navigation Co's *Eastern Glory* (Fig. 8.4), Hong Kong and China-based ship portraitists contributed to a marvellous visual record of the development of the steamship. It is an amazing catalogue of the changing appearance and size of steam-powered ships.

But we should take care to see what else the rise of this sort of art shows us. It is the endorsement of the new technology and its cementing as a normal and important feature in everyone's lives. In that sense, art's role in the triumph of steam power at sea should never be overlooked.

We can see that by contrasting the treatment of steam power at sea in the Western tradition which, whilst it also gloried in the utter beauty of the sailing ship, treated steam with respect, and more, with how steam was initially artistically received in Asia. Steam was seen in every respect as not merely alien,

but as visually almost incomprehensible. That applied across the board, whether at the level of explanatory statements by important figures like Lin Zexu (林則徐) or Qiying (耑英), trying to come to terms with this strange but powerful technology, or with visual artists trying to depict something they simply couldn't get to grips with.

Here's Lin Zexu:

"There were two wheel ships with a funnel. The ship has two masts. Its length is more than twenty-odd zhang [more than 64 metres] and width more than two zhang [more than 6.4 metres]. The funnel ship has two wheels hung outside its broadsides. The ship's cabin stores a square furnace under the beam from which the wheels are hung. When the fire is burning in the furnace, the two wheels turn like a fast mill and the ship cruises as fast as if it is flying, regardless of the wind's direction."

Qiying was equally baffled:

"The length of the fire-wheel ship I boarded is about five zhang [about 16 metres] and the width of it is half of the length. The ship is fitted with a water and a fire cylinder. When coal is burnt [in the fire cylinder], fire flares and smoke rises. Both inside and outside [of the water cylinder] there are gears, which are agile. [The fire cylinder] is roughly based on the law of the clock. Hence [the ship] can cruise fast without the sail. It is rumoured that there are men or oxen driving the gears. But this is speculation."

The two brilliant officials' bafflement, which was shared by almost all Chinese

and other Asian observers of this bizarre new phenomenon, can also be seen in the work of Chinese and Japanese artists portraying Western vessels to their local audiences (Fig. 8.5 & 8.6).

Even people like Ding Gongchen (丁拱辰), arguably the first person in China who seems actually to have understood that it was steam, not fire, smoke, men or oxen that drove the machinery that propelled the Western ships, and who had developed a sound grasp of how things worked, was quite unable to get the artist he used to draw accurately and informatively what he was trying to explain (Fig. 8.7). There was no such drawing tradition.

But as we can see, as early as the arrival of the steam tug *Forbes* in 1830, gifted Chinese artists like Sunqua were entirely capable of accurate depictions when that was what their clients demanded. So why was the work of Chinese and Japanese artists for their domestic audiences seemingly so inaccurate?

We cannot know for sure. The probabilities are three: one is the ruling set of artistic conventions with which creative work must conform to be acceptable. That's why working for Westerners was so different — they weren't expected either to want or to understand Chinese or Japanese conventions. Another related probability is that when an artist's potential audience not only entirely lacks the visual and other vocabulary necessary to 'see' and understand what is depicted, and is also understood to be in some important sense both hostile to and dismissive of the importance of what is being portrayed, the portrayal inevitably shows this by way of a form of caricature. And finally, of course, accurately painting a steamship is one thing. Being able to depict the details that show the working

principles of its propulsion system accurately is something else entirely.

The point is simple: art can and does play a very important role in the advancement of any new technology. It does so as a direct contributor in technical drawing. It does so as an active and helpful propagandist through commercial and graphic art. It does so above all when the artist sees the new technology as a vibrant and integral part of their own world, though not always necessarily a fully positive part, and portrays it as such. The wide and full embrace of steam power by artists of all kinds in the 18th- and 19th-century Western world — even when, like the English novelist Charles Dickens, that embrace was reluctant and apprehensive — is an essential aspect of the triumph of steam.

怎麼說呢？

任何重要的技術改革能夠興盛的原因，是因為它同時得到決策者和平民大眾的廣泛接受。我們一方面看看近來核能發電的命運，而另一方面參考一下汽車的成功。因為無知和誤解，任何重要的創見都被視為必然是破壞性的，會構成威脅的。面對全新的事物，人們一向看待事物或行事的習慣或多或少地首先抱質疑態度。1830年代的歐洲，很多人當被告知新的鐵路列車能夠以每小時30英里（每小時48公里）的速度運載乘客後，都覺得這種速度會讓人不能呼吸。因此，關鍵是那些社會精英和影響輿論的人，如何對待任何革新。創意活動的各個領域例如繪畫、建築、雕塑、文學、音樂、戲劇和其他表演等都會對構築民意起重要作用。

藝術家（普遍被理解為社會文化生活的貢獻者）及其世界通常被理解為與科學、技術、數理等世界對立。某程度上一直也是如此，甚至直到今天。可是，就如我們在本文中看到的很多例證，藝術往往很努力地在蒸汽的使用方面發揮作用。畢竟藝術家經常視自己為激進的創見者。

舉個例子，視覺藝術如何可以能令蒸汽動能的世界出現，答案再明顯不過，就是機械繪圖及其於精密工程學中所扮演的角色。同樣明顯的是18至19世紀歐洲極速擴展的商業印刷——無論是售賣給越發富裕的中產階級以供他們裝飾房子（如響尾蛇號和阿萊克托號的畫像）的畫作、書本和告訴他們新世界已經來臨的新聞所附上的插圖（譬如復仇女神號的畫像），還是商業廣告界的增長（如亞倫·曼比號的廣告），都是如此。的而且確，美國人理查·霍（Richard M. Hoe）在1843年發明以蒸汽推動旋轉的印刷機之後，甚至連大量生產的圖像本身也越來越依賴蒸汽進行打印，並依靠由蒸汽驅動的火車分發。

有時被稱作「高級」藝術界別裡的人，在蒸汽動能興起的故事中既對這新發明存有敵意，同時也有支持這些怪異奇妙的新機器

及其變革潛質。瑪麗·雪莉是經常被誤解的19世紀初小說《科學怪人》的作者，她的另一部書是《The Modern Prometheus》，兩部書標榜科學和科技為英雄。瑪麗嫁給了浪漫主義詩人珀西·比希·雪萊（Percy Bysshe Shelley）。對他們兩人來說，科學和技術都是英雄，雖然有時帶有缺憾，而不是惡棍。比方說，珀西·雪萊是蒸汽的狂熱愛好者，他在意大利經濟支援了試圖設計和製造航行於法國馬賽與意大利利佛諾的商用蒸汽船的朋友雷佛利（Henry Willey Reveley）。後來到1822年，這就是他在一次海上事故喪生的地方。

這種認為蒸汽是需要被讚頌而非被譴責的態度，在透納（J.M.W. Turner）的視覺藝術作品中也許最為人所知。他讓人嘆為觀止的作品《暴風雪中一汽船駛離港口》（1842年）把新科技置於畫的正中央（圖8.1）。

再談談透納，因為他的另一幅畫作可以向我們說明兩件事。其一是有關航海的藝術不單令蒸汽動能變得熟悉和可接受，更是值得頌揚和感到自豪的事物，即使我們可能會為這過去的世界被淘汰而感到遺憾。其二是被我們稱為中國海岸或中國出口藝術家的作品，如何在中國海岸世界中扮演這種角色。

透納的一幅早期畫作完美地展示了藝術是如何表現海洋蒸汽動力的變革性質素，和與它正在取代的航海世界的聯繫。透納1838年的畫作《被拖去拆毀的戰艦無畏號》（圖8.2），再次讓海上蒸汽新世界成為焦點。不過他是透過呈現蒸汽平凡、日常、次要角色（例如利用拖船）的方式達到這種效果——相對於19世紀中人們曾經在英國看過他的畫作，是那麼直接地描繪在全球海上主導地位中崛起的英國皇家海軍18世紀末和19世紀初木製帆船戰艦的超強戰鬥力。

要注意的重點是，透納展示的是一個非常平靜的海，連一點風都沒有的大海。從煙囪生出的煙我們可以看到，那是艘蒸汽帆船拖曳著曾經盛極一時卻已衰敗的風帆戰艦（完全不受無風的影響），它保留著的那幾塊已經無用的帆被捲起收好。離右邊一點的

中心處，另一艘飄著煙的蒸汽帆船，正在拖曳一艘船，船上的所有帆都向上揚起。靠近無畏號（*Temeraire*）及其拖船的右側是兩艘帆船，一艘運作中、後桅的帆寬鬆地懸掛著的駁船，正順著浪潮緩緩離開；而在遠處，一艘橫帆的船正離開河流，揚起了所有的帆飄移著，卻因無風而幾乎處於停泊狀態。蒸汽是未來，雖然看上去黑壓壓的且有點醜陋，風帆正慢慢飄移淡出……或者，被拖曳到最後的安息之地。

這是非凡的天才藝術家所呈現的景象。更多平凡的、試圖靠著取悅顧客為生的藝術家，只有全然單一的視覺。畫作是由船長或船主委託繪畫，若主題是蒸汽船的話，隨著它於19世紀的陸續發展，畫中的船便應該從其壯觀的排場中展現出來。

在香港，其中一艘最早的本地蒸汽船是由美國船長James Bridges Endicott駕駛、往來香港與廣州的小輪的火花號（*Spark*）（圖8.3），自從1855年這艘船的畫像開始，直至1949年怡和洋行印華輪船公司（Indo-China Steam Navigation Co）的耀東號（*Eastern Glory*）的景像（圖8.4），紮根於香港和中國的船舶肖像畫家們都為蒸汽船的發展獻出不少讓人讚嘆不已的視覺紀錄。這是蒸汽動能船的目錄，顯示了船隻在外觀和尺寸上不斷變化。

不過我們應該仔細留意這種嶄新的藝術呈現了甚麼給我們。這是對新技術的認可，並將之鞏固成為每個人生活中的日常和重要角色。在這個意義上，藝術在海上蒸汽動能的重大成功中所扮演的角色，絕對不能被忽視。

要理解上述觀點，我們可以與西方傳統對蒸汽航海的處理作對比，一方面欣賞帆船的美感但同時也尊重亞洲以藝術方式接受蒸汽及其技術。蒸汽之於後者，在每個方面都不單被視為異類，在視覺上更幾乎是無法被理解。正如重要人物林則徐或耆英等對這技術的解說中，試圖讓自己慢慢接受這個陌生但先進的科技，或者畫師們正嘗試描畫一些他們基本上不能掌握的事物。

林則徐如是說：「那是兩艘附有煙囪的輪船。那船有兩支桅杆。其長逾20丈（超64米），寬逾2丈（超過6.4米）。煙囪船的船側懸掛著兩個輪，船的船艙內、掛著兩個輪的船寬下方，安裝有一個方形的火爐。當火爐裡的火燃燒，兩個輪子就會如快速的石磨般轉動，船便像飛一般快速航行——無論風向如何。」

耆英同樣感到困惑：「我登上那艘火輪船約長5丈（大概16米），其寬度是長度的一半。船上各有一個火缸和水缸。當煤（於火缸內）燃燒時，火光紅紅，輕煙裊裊。（水缸的）內外都有靈活的齒輪。（火缸）大致以時鐘定律作為基礎。因此（船）能夠在沒有帆的情況下航行得很快。有傳言說是有牛在推動齒輪，但這是推測。」

這兩位偉大官員的疑惑，在中國和日本的畫家為當地觀眾所繪畫的西方船舶作品中亦能看到，這種疑惑幾乎是所有中國和其他亞洲人在觀察這種新的奇怪現象時共有的（圖8.5 & 8.6）。

即使是丁拱辰（可以被視為第一位中國首個了解驅動西方船隻的是蒸汽，而非火、煙、人或牛，並對於事物的運作已發展出充份理解的人），也不能令他顧用的畫師明白他的解說而畫出帶有精確資料的圖（圖8.7），因為當時中國並沒有這種繪畫傳統。

不過，正如我們所見，早於1830年蒸汽帆船霍布斯號（*Forbes*）抵達時，順呱等天才中國畫家已經能按顧客的要求精確地描繪船舶的圖像。那為何中日兩國藝術家為他們的國內觀眾所繪畫的作品，看起來卻如此不精準？

我們不能完全知道，但可能性有三。其一是藝術圈約定俗成中的支配性規則，藝術家必須遵循，其作品才能被接受。這就是為甚麼為西方人作畫時會如此不同——因為人們不會期望他們想要或者明白中國或者日本的約定俗成。另一個相關的可能性是，當該畫家的潛在觀眾，不只全然缺乏「看」或理解作品中所描繪事物所需的視覺或其他詞彙，同時在某程度上敵視和輕視所

被繪畫的事物，畫像本身便無可避免地展現出這一點。最後，想當然爾，精確地繪畫蒸汽船是一回事，要準確地描繪能夠呈現推進裝置運作原理的細節，則完全是另一回事。

重點很簡單，藝術在任何新科技的發展上都扮演著十分重要的角色。它既是技術繪圖的直接貢獻者，也是因著商業和圖像藝術而成為積極的宣傳者。藝術能做到以上種種，是因為藝術家把新科技視作讓其世界變得生氣盎然，也更完整的部分（儘管這部分不一定完全正面），並以此繪畫。18至19世紀西方社會各界藝術家對於蒸汽動能廣泛而全面的擁護（即使像英國小說家狄更斯所形容般，這擁抱是勉強而帶憂慮的），是蒸汽能站穩的關鍵。

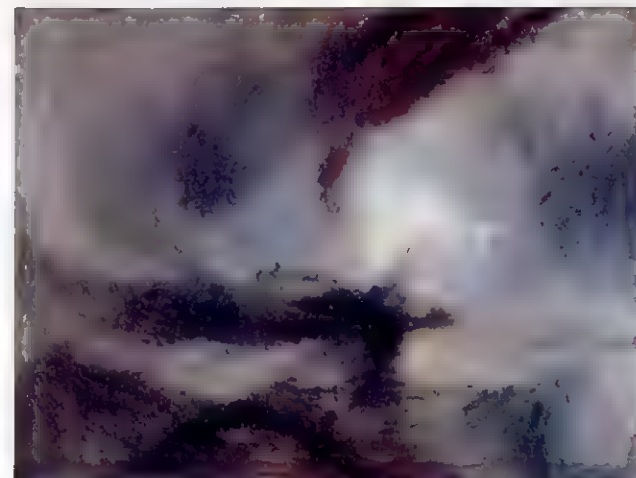


Figure 8.1: J.M.W. Turner,
Snow-Storm — Steam-Boat off a Harbour's Mouth (1842).
(Source: <https://www.tate.org.uk/art/artworks/turner-snow-storm-steam-boat-off-a-harbours-mouth-n00530/>)

圖 8.1：透納的畫作《暴風雪中一氣船駛離港口》，1842 年。
資料來源 維基百科 <https://www.tate.org.uk/art/artworks/turner-snow-storm-steam-boat-off-a-harbours-mouth-n00530/>)

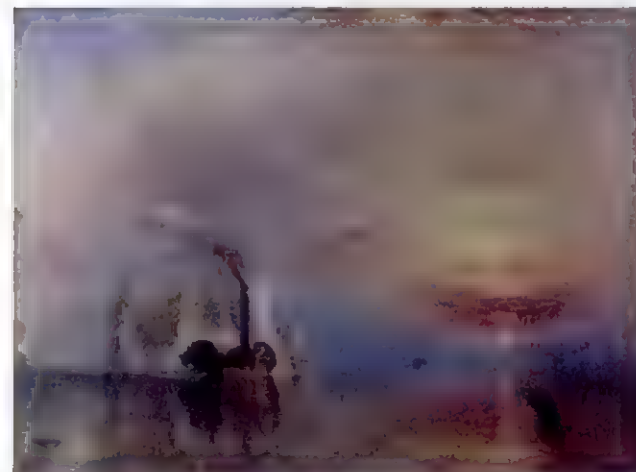


Figure 8.2: J.M.W. Turner, *The Fighting Temeraire, tugged to her last berth to be broken up, 1838*. (1839)
(Source: <http://www.nationalgallery.org.uk/paintings/joseph-mallord-william-turner-the-fighting-temeraire/>)

圖 8.2：透納的畫作《被拖去拆毀的戰艦無畏號》，1838 年。（1839 年）
資料來源 <http://www.nationalgallery.org.uk/paintings/joseph-mallord-william-turner-the-fighting-temeraire/>)



Figure 8.3: Tingqua studio (Guan Liangchang), View of the waterfront at Canton with the paddle steamer 'Spark', (1855).
(Source: Hong Kong Maritime Museum.)

圖8.3：庭呱（關聯昌）畫室，「於明輪船火花號（Spark）上欣賞廣州的海濱」，1855年。
（資料來源：香港海事博物館。）



Figure 8.4: 'Ling' (Kam Cheong-ling), Indo-China Steam Navigation Co's *Eastern Glory* (c.1949).
(Source: SNGD digital image collection.)

圖8.4 甘長齡，印華輪船公司的耀東號（約1949年）。
（資料來源：SNGD數碼圖像收藏。）



Figure 8.5: Unknown Chinese artist's view of the HEIC *Nemesis* (c.1844) — the crew are in 18th century clothing!

(Source: <http://www.chinainprint.com/opium-war-watercolour-album/>.)

圖8.5：佚名中國畫家眼中的復仇女神號——船員穿著18世紀的服裝！（約1844年）
（資料來源：<http://www.chinainprint.com/opium-war-watercolour-album/>。）



Figure 8.7: Ding Gongchen, A steam engine, piston, cylinder valve system and output crank.
(Source: Hathi Trust: *Yanpao tushuo jiyao* (演藝圖說輯要), Quanzhou: Hu wen tang, 1843, p.275.)

圖8.7：丁拱辰，蒸汽引擎、活塞、氣缸閥門系統和輸出曲柄。
（資料來源：《演藝圖說輯要》，泉州：會文堂，1843，頁275。）



Figure 8.6: Japanese artist's view of one of US Commodore Perry's steam-driven Black Ships.

(Source: Detail from British Library manuscript Or.16453 *1853, An untitled scroll depicting the arrival of the squadron of ships under the command Commodore Matthew Perry at Uraga Bay, Japan in July 1853. The coloured illustrations include the personnel, equipment and ships, the composition of the naval procession, official ceremonies at Kunhama and a view of Uraga Bay." at http://www.bl.uk/manuscripts/Viewer.aspx?ref=or_16453_f001r. Copyright free at <https://blogs.bl.uk/asian-and-african/digitisation/>.)

圖8.6：日本藝術家眼中的美國海軍準將培理（Matthew C. Perry）掌舵的蒸汽黑船。
（資料來源：大英圖書館手稿Or.16453，「1853，無標題的卷軸，描繪了海軍準將馬修·培理麾下的海軍艦隊於1853年7月抵達日本浦賀灣。彩色插圖包含船員、設備和船隻、海軍隊伍的組成、久里兵的官方儀式及浦賀灣的景色。網址為http://www.bl.uk/manuscripts/Viewer.aspx?ref=or_16453_f001r。
<https://blogs.bl.uk/asian-and-african/digitisation/> 免費提供版權。）



海上蒸汽 動能的未來

THE FUTURE OF STEAM POWER AT SEA

The long and complex development of the marine steam engine was a quest to solve the key problems that the acute minds of pioneering 18th century engineers like John Smeaton and James Watt could see. How could the engines be made more efficient and more powerful? In the two centuries that followed the installation of Thomas Newcomen's under 5hp, very inefficient engine to the four steam turbines that produced 68,000 shaft horsepower for the transatlantic passenger line *Mauretania* that went into transatlantic service in 1907, the developments were extraordinary.

海上蒸汽引擎那漫長而複雜的發展，是為了解決18世紀先進工程師如斯密頓和瓦特等敏銳頭腦所能看到的關鍵問題：如何能夠令引擎更高效和強力呢？紐科門那非常低效、低於5馬力的引擎，到兩個世紀之後，演變成1907年起從事橫越大西洋服務的客運路線毛里塔尼亞號（*Mauretania*）配備安裝了68,000軸馬力的4個蒸汽渦輪，這是十分非凡的發展。

The simple, single cylinder piston of Newcomen's atmospheric engine was transformed by James Watt's introduction of a dual action piston. Then came compound engines with two cylinders in the 1840s... then three in the late 1870s (Fig. 9.1a & 9.1b) ... and even four by the end of the 19th century. Thanks to steady improvements in boiler design, the consumption of fuel was cut from 14.5kg of coal an hour for every horsepower developed to just 0.61 kg/hp/h (Fig. 9.2).

At that point in the early 1890s, a man called Charles Parsons invented the steam turbine (Fig. 9.3). Like everything we have looked at so far, this was another bringing together of ideas that had been around for many years by someone with the genius not just to see how to put them to a new use (Fig. 9.4), but with the engineering brilliance to design the machinery. Great success though Parson's turbines were, their cousins are still providing much of the world's electricity — it was almost the last hurrah for steam power at sea (Fig. 9.5).

The reason for that is simple and takes us back to that quest on which John Smeaton and James Watt and every other boiler and engine designer was engaged. For all its triumphs, the steam engine had developmental limits. Even with the most efficient steam boiler — like the Admiralty 3-Drum and its successors — and the fully developed steam turbine, the very best efficiency a steam engine at sea managed was as shown in Figure 9.6.

You can see from the table how the invention of the diesel engine by Rudolf Diesel in 1893, and its first use at sea in the French submarine *l'Aigrette* in 1902, would threaten the future of steam (Fig. 9.7). The threat proved real but, as we saw in Chapter 1, it took another half century before the diesel engine finally

replaced the steam engine on ships.

It is possible that steam power could achieve 50% efficiency with the almost incredible high-end steam temperature of 730°C and pressure of 5076.3 psi (34998 kPa). Electricity power stations — today the main users of steam turbines that produce 89% of the world's electricity — are aiming at this and already operate at 3626 psi (25000kPa) and 565 °C and achieve <45% efficiency. But what can be done in a massive power station is unlikely to be scalable for use at sea unless, perhaps, nuclear power could step in.

At present the pressurised water reactors in use at sea produce steam at 275°C at 900 psi (6205 kPa) with an efficiency in the same range as modern diesels. In theory, therefore, nuclear power could have seen the comeback of steam power at sea. As we have seen, however, costs and public attitudes to nuclear power have, bar experiments like the *Savannah* (1962–1972), the German *Otto Hahn* (1964–1979), the Japanese *Mutsu* (1972–1992) and the Russian *Sevmorput* (1988–) kept it restricted to military and equivalent use. Indeed, it was military use in submarines, since it allowed a true submarine for the first time as opposed to a submersible,²⁴ that saw nuclear steam power first go to sea and, indeed, that pioneered the entire concept of the nuclear-powered steam generation subsequently used in nuclear power stations. The pioneers were the Americans, driven by the father of nuclear power at sea, US Navy Admiral Hiram G. Rickover, who oversaw the reactor program and then the building of the world's first nuclear powered vessel, the submarine USS *Nautilus*, that was first commissioned in 1954 (Fig. 9.8).

24 A submarine, strictly, should be able to submerge and stay underwater for the entirety of its mission once it has left port. Pre-nuclear vessels, for any extended cruising, were always dependent on an air-supply for the diesel engines that were their main means of propulsion. Nuclear submarines are released from that constraint and, thanks to clever air cleaning systems, can constantly remove the CO₂ from the air to ensure an air supply for their human crew.

紐科門氣壓引擎的簡約氣缸活塞，是由瓦特推出的雙重作用活塞改良所得。然後複式引擎於1840年代開始擁有兩個氣缸……隨後是1870年代末期的3個氣缸(圖9.1a & 9.1b)。19世紀末甚至發展到4個。由於鍋爐設計的持續改進，燃料消耗量由每小時每馬力的14.5公斤煤，減至僅僅每小時每馬力0.61公斤(圖9.2)。

在1890年代初期，帕爾森斯(Charles Parsons)發明了蒸汽渦輪(圖9.3)。就如目前我們所檢視過的敘述，是把已經存在多年的構思融合起來——他不僅發現了這些構思的新用法(圖9.4)，更以工程學的才華設計出相關機械，儘管帕爾森斯的渦輪擁有莫大成功(而它們的家族成員至今依然為世界提供大量電力)，但這幾乎已是海上蒸汽動能最後的喝彩聲(圖9.5)。

原因很簡單，且讓我們回到斯密頓、瓦特及所有鍋爐、引擎設計者的探索。撇除技術的成功開發，蒸汽引擎仍然有發展上的極限。即使是最有效率的蒸汽鍋爐(如英國海軍的三筒式鍋爐及其後繼產品)，以及已全面發展的渦輪，效率最佳的船用蒸汽引擎也只能如圖9.6所顯示般。

在對照表中可以看到1893年由狄塞爾(Rudolf Diesel)發明的柴油引擎，在1902年首次用於法國潛艇白鷺號(*l'Aigrette*)，其效能足以威脅蒸汽動能的未來(圖9.7)。正如第一章提到的，這個威脅在半個世紀後成真，柴油引擎最終取代了蒸汽引擎。

當蒸汽溫度達到高層次的攝氏730度，以及每平方吋5076.3磅(34,998帕斯卡)壓力，蒸汽動能達到50%的效率是可能的。發電站(是今天蒸汽渦輪機的主要用戶)需要的正是這樣的效能，且已經能夠做到每平方吋3,626磅(25,000帕斯卡)和攝氏565度的溫度，達至逾45%的效率。可是，除非有核電介入，否則在大型發電廠能做到的工作根本不可能應用到船上。

如今，壓水反應爐應用於船上時，能以與現代柴油相同範圍的高效率，即攝氏275度和每平方吋900磅(6,205帕斯卡)

產生蒸汽。因此，核能理論上是能夠讓海上蒸汽動能回歸的。不過，正如我們所見，核能的成本和社會接受度——透過如薩凡納號(*Savannah*) (1962–1972)、德國奧托·哈恩號(*Otto Hahn*) (1964–1979)、日本陸奧號(*Mutsu*) (1972–1992)、俄羅斯北方航道號(*Sevmorput*) (1988–)等的實驗——讓其僅限於軍事或相關用途。實際上是軍事潛艇的用途，因為對比起潛水器，這是第一艘真正的潛艇²⁴；亦是核能蒸汽動能首次應用於海上，並且繼核電站用途之後，開拓了整個核能蒸汽世代的概念。開創此先河的是美國人，且由海上核動力之父、美國海軍上將李高佛(Hiram G. Rickover)帶領。他監督了反應堆計劃，並在1954年建造了世界上第一艘核動力潛艇鸚鵡螺號(*USS Nautilus*) (圖9.8)。

24 嚴格來說，潛艇離開港口就應該能夠潛入水中並留在水底直至完成任務。對於使用核能前的船隻，若需延長航行時間，總是依靠向柴油引擎供氣作為主要推進方式。核潛艇擺脫了這種束縛，全賴採用了巧妙的空氣淨化系統不斷除去空氣中的二氧化碳，以確保為船員提供空氣。

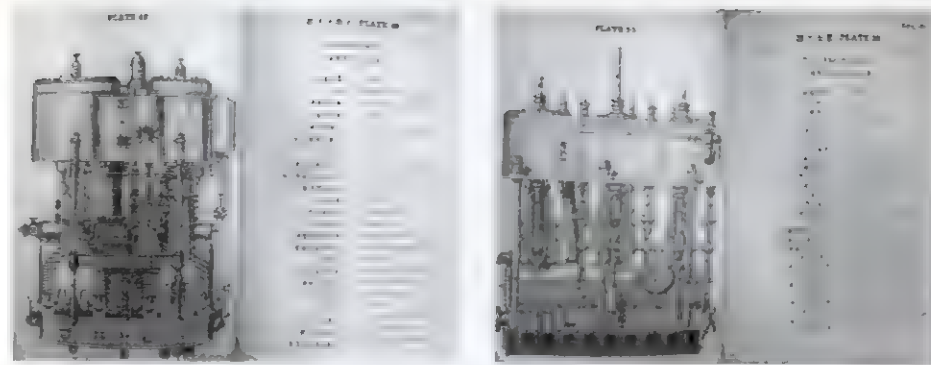


Figure 9.1a, 9.1b: Compound and triple-expansion marine engines from the first ever Chinese-English maritime dictionary.

(Source: JHP Parker, *Anglo-Chinese glossary of terms used in shipbuilding, marine, engineering, rigging, etc.*, Shanghai, 1894)

圖9.1a、9.1b：最早的漢英海軍辭典中的複合及三段膨脹式船用引擎。
(資料來源：派葛(JHP Parker)·《輪船類事圖考》·上海 1894年。)



Figure 9.2: SS *Aberdeen*, the first large ship fitted with a triple-expansion steam engine.

(Source: State Library of Queensland, http://rosettadel.sq.qld.gov.au/delivery/DeliveryManagerServlet?change_ing=en&dps_pid=IE1084098/)

圖9.2：鴨巴甸號——第一艘裝有二段膨脹蒸汽引擎的大型船舶。

(資料來源：昆士蘭州立圖書館，http://rosettadel.sq.qld.gov.au/delivery/DeliveryManagerServlet?change_ing=en&dps_pid=IE1084098/。)



Figure 9.3: The *Tenyo Maru* — the first steam turbine powered liner built in Asia that visited Hong Kong in June 1908.²⁵

(Source: SNGD collection.)

圖9.3：天洋丸——第一台於亞洲建造、由蒸汽渦輪驅動的遊輪，並曾於1908年6月造訪香港。²⁵
(來源：SNGD系列。)

25 The first steam turbine in China, imported from the Parsons' works in Britain, was a 1,350hp engine for the Municipal Electricity Works in Shanghai, that first operated as an experiment on 1st September, 1907.

25 中國第一台蒸汽渦輪機由帕爾森斯在英國的工廠進口，具備1,350馬力的引擎，上海市政電力公司於1907年9月1日首次試行。



Figure 9.4: Charles Parson's revolutionary, turbine powered *Turbinia* in 1894.
(Source: Courtesy of Siemens archive via <https://dec3uk.org.uk/turbinia.htm> and Wikipedia.)

圖 9.4：1894 年，帕爾森斯的革命性、由渦輪驅動的透平尼亞號。
(資料來源：<https://dec3uk.org.uk/turbinia.htm> 及維基百科。)



Figure 9.5: The *Prince Edward*, the world's first commercial ship powered by a steam turbine, launched 1901.
(Source: Wikipedia, public domain, anon. "The turbine steamer TS King Edward on trials in the Firth of Clyde off Skelmorlie, between 17 and 28 June 1901.")

圖 9.5 1901 年啟用的世上第一艘以蒸汽渦輪驅動的
商用船愛德華王子號
(資料來源：維基百科，公共領域，匿名。「渦輪機輪船愛德華王子號(T.S. King Edward)於1901年6月17至28日間，在新凱爾莫利對出的克萊德灣首航啟航。」)

Type	Efficiency
Triple Expansion	11%
Quadruple Expansion	13%
Turbine	14%
2-stroke diesel	29%
4-stroke diesel	31%

Figure 9.6: Comparative efficiency of ship propulsion systems.
(Source: Created by Stephen Davies.)

圖 9.6：船舶推進系統的相對效率。
(資料來源：由史提芬·戴維斯繪製。)



Figure 9.7: The world's first diesel powered vessel the French Navy's *l'Aigrette*, c.1902.

(Source: Wikipedia, photographer Marius Bar, photograph unknown date c 1902)

圖 9.7：在約 1902 年，世上第一艘柴油動力船，法國海軍的白鸞號。
(資料來源：維基百科，攝影師 Marius Bar，拍攝日期未知，約 1902 年。)

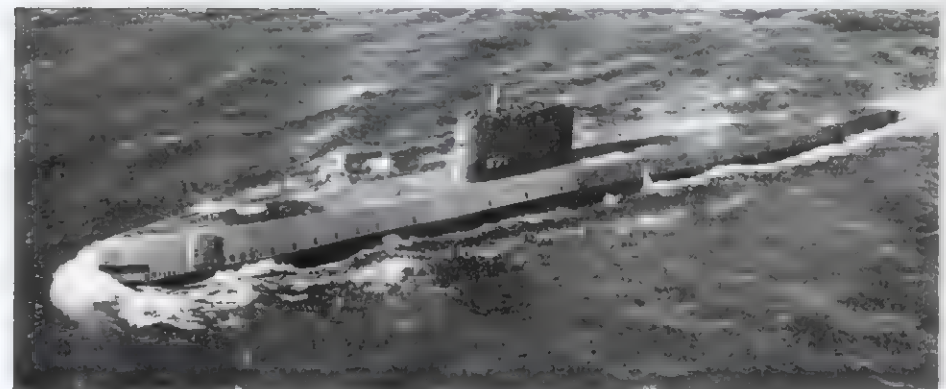


Figure 9.8: The USS *Nautilus* on trials in 1955.
(Source: Wikipedia from the US National Archives copyright free see <https://catalog.archives.gov/id/521003/>.)

圖 9.8 鸚鵡螺號於 1955 年進行測試。
(資料來源：美國國家檔案館的維基百科，免費版權
請參閱 <https://catalog.archives.gov/id/521003/>。)

10

科學創意的
「結蒸」CLOUDS OF
S.T.E.A.M.

From the beginning to the end of the story of steam at sea, what we have been seeing is a complex dance between science, technology, engineering, art and mathematics. But the various dancers have never been clearly distinguishable. Many of the people mentioned were simultaneously doing science, engineering, technology and mathematics... and, for example in the drawings of James Watt or William Symington and in the writings of most of them, art as well.

海上蒸汽故事由開始到終結，我們看到的是科學、科技、工程、美術和數理次第出場的群舞。然而各個舞者之間並不能明確區分。很多故事中提及過的人物，其實都同時從事於科學、工程、科技、數學……例如瓦特和希明頓的繪圖、文字作品，以及藝術作品等等。至此，多數海事工程的偉大成果都來自與海事事務無關的人。以帕爾森斯為例，他於1889年在英格蘭紐卡素爾創立的公司C. A. Parsons and Company，旨在生產他設計的渦輪發電機。把渦輪用於驅動船隻是我後來的事，也許因為他的渦輪發電機起初實在太低效吧！發明出第一代船用螺船槳的人是個鐘錶匠，此外還有很多類似的例子。

As much to the point, many of the great triumphs of marine engineering were the achievements of people who didn't start out with a maritime project. Charles Parsons, for example, founded his first company, C. A. Parsons and Company, in Newcastle, England, in 1889 to produce turbo-generators he'd designed for producing electricity. Using the turbines to drive ships was something of a later add-on, perhaps because his turbo-generators were initially very inefficient! The man who devised the first marine propeller was a watch and clock maker. There are many similar examples.

We can see what this means clearly, and bring this book to an end, by looking at the first steamship ever built in China to a Chinese design by Chinese engineers. It is an interesting example of the intricate dance of S.T.E.A.M. by people who arguably didn't think in such terms at all. After all, as we can see from the Google Ngram in Figure 10.1, such terms can't be said to have existed in Chinese when China first encountered the steam engine, and its ingenious thinkers and doers who realised what was at stake began the race to catch up. Rather, how knowledge was thought of was in terms of the Six Confucian Arts (六藝) and, to begin with at least, the new ideas flowing in from the intrusive Western world had to be fitted into that older framework.

We can see this at work by looking at another Ngram, of what terms filled the gap in the traditional vocabulary, namely the dominant member of the three general terms used to deal with all this new sort of knowledge coming in: *bowu* (博物) = natural science, but originally ideas transgressing the boundaries of the defined canons of knowledge; *gezhi* (格致) = investigation of things or studying the underlying

principles, co-opted in the late Qing to refer to Western science; and *kexue* (科學) = science, scientific knowledge. The dominant member, in the Ngram at least (Fig. 10.2), is the last and you can see, comparing it with the advent of the new way of thinking of something called 'mathematics' (數學) as opposed to Confucian 'counting' (數), how both new terms flourished in the critical period from just before the First Opium War until the years after the end of the Second Opium War and the rapid expansion of the Treaty Ports through which so much of the new knowledge came flooding in. That was especially true of marine engineering as a result of the nine Western owned and operated dockyards in Shanghai by the mid-1860s, three in Hong Kong, four in Guangzhou's Huangpu and within a decade or so dockyards, both Chinese and foreign owned, in Xiamen, Fuzhou, Chefoo (Yantian) and elsewhere as well.

We end by seeing how the long transformation in Western thought that led to the understanding of steam as a gas like any other gas was partly mirrored yet massively compressed in China as two ancient concepts: *qi* (氣), an animating spirit, and *zheng* (蒸), the everyday, wet steam one cooked with, were combined into a new concept, *zhengqi* (蒸氣) as part of embracing steam power in China (Fig. 10.3). They had to deal with a new way of seeing things vital to understanding how a steam engine worked, instead of relying, as everyone had before Ding Gongchen, on the traditional ideas of the *wuxing* (五行). That's because the implicit incompatibility of fire and water in traditional cosmology meant that anything trying to combine them in some way, as a steam engine seemed to, was unlikely to work. Another way of seeing that is to remember that steam in a high

pressure steam engine is a *dry gas*, quite unlike the wet steam that cooks food, and the concept of steam as a dry gas simply can't be derived if one works from the principles of the *wuxing*. Hence *zhengqi*.

In 1861, Xu Shou (徐壽) and Hua Hengfang (華蘅芳) were commissioned by Zeng Guofan, Marquis Yiyong (曾國藩), the Viceroy of the Liangjiang (today's Jiangxi, Anhui and Jiangsu provinces), to build a steamer (Fig. 10.4). Of course, neither man really had any practical idea how this was to be done it. Why should they have done it? It is known that Xu had been interested in the new Western mechanical engineering since at least 1855, when he was 43. Equally Hua, 15 years younger, had specifically focused on mathematics. However, James Watt's advantages almost a century earlier, a tradition of experimental science, Western technical drawing conventions, early machine tools and early precision engineering, do not seem to have been skills and techniques either Xu or Hua had mastered or acquired until they were recruited by Zeng Guofan in 1861. Equally, how much actual practical engineering either had engaged in before that point as a result of their interest is unknown.

What does seem to be known is that Xu and Hua had both spent some time studying the many volumes of introductions to and translations of contemporary Western science by the London Missionary Society's Alexander Wylie, translated by Li Shanlan (李善蘭) and published by the Inkstone Press (*Mohai Shuguan* 墨海書館) in Shanghai. The relevant volume for the steam engine was one of a series of works by the missionary, Dr Benjamin Hobson, published as of 1849, specifically the 1851 *Bowu xinbian* (博物新編, *Treatise of Natural*

Philosophy) that amongst much else had a chapter that explained the principle and mechanism of the steam engine, including some basic diagrams of the stationary engine and its parts (Fig. 10.5).

Both Xu and Hua were very clever men and, like sufficiently motivated clever people anywhere, obviously came to understand what needed to be done, although this took them almost a year. Clearly they must have had access to a great deal more than Hobson's book, and we know they visited foreign steamers in the Yangzi near where they were working. Interestingly, they seem then to have followed the very traditional Chinese route of building a scale model first. The tiny little model engine of 1862, with a 43mm diameter cylinder, hummed along satisfactorily at 240 revolutions a minute, although we are not told how the steam was created.

Building a model, however, is a very different matter from building a full-sized steam engine, even a fairly small one. For the model, traditional craftsmen's tools would have been sufficient. For a full-sized steam engine more would be needed. Much more. Indeed, it took three more years and at least one failure — the small boat managed just over half a kilometre before it ran out of steam because Xu and Hua still hadn't fully grasped how a boiler worked — before a successful, though at eight metres long still small, paddle steamer completed its trials in 1865.

It seems probable that, in order to achieve what they did, Xu and Hua had access to some Western machine tools and something like a drawing office. We know they imported some components and it seems probable that they used the imported Western machine tools and workshop facilities that had been bought in 1864 by Li Hongzhang's aide, Samuel

Halliday Macartney, from the ships of the Lay-Osborne Flotilla before they were sent back to Britain.²⁶

It was all very well to have recourse to Hobson's book but, as Figure 10.4 shows, what that illustrated was woefully insufficient for producing what Xu and Hua built. It follows that there is much about the story of the *Huanghu* (黃鵠, *Yellow Swan*) that we do not know and that would affect our understanding of exactly how Xu and Hua achieved as much as they did. After all, manufacturing a boiler with its copper water tubes, the cylinder, piston, connecting rods and journals, crankshaft of the engine, and all the smaller components like nuts, bolts and valves would have required drawings, precision measuring instruments, foundry skills, lathes, drills and much else besides, not just traditional Chinese carpenters' and metal workers' tools and measuring devices.

But no matter what the details actually were, with the successful launch and maiden voyage of the *Huanghu*, China had taken the first steps towards compressing into a few decades some 300 years of development in the Western world of the vast mix of S.T.E.A.M. learning and skills we have been following. The result would be that by the end of the 19th century China had more or less caught up and joined the steam revolution the world was undergoing.

In Xu Shou (徐壽) and Hua Hengfang (華蘅芳), who had to be scientists, technologists, engineers, artists and mathematicians all at once, we see that S.T.E.A. and M. cannot really be separated. They are an interacting whole, a complex dance of myriad partners spinning and turning, backwards, forwards and sideways, sometimes stopping, sometimes

reversing, always moving. Xu Shou had obviously realised this, and that a modern China needed it, which is why, helped by Walter Medhurst, the then British Consul in Shanghai, he founded his Gezhi College (格致書院) in the Shanghai Foreign Concession in 1874.²⁷

26 Sir Samuel Halliday Macartney, one of the first foreigners to become a Chinese civil servant, was a relative of Lord Macartney of the famous failed British embassy to China of 1793.

27 Today Shanghai Gezhi Middle School (上海市格致中學).

到此書的結尾，現在我們來看中國工程師於中國設計和建造的第一艘蒸汽船，這讓我們清晰地了解以上所說的有何意義。對於「S.T.E.A.M.」這段錯綜複雜的群舞，它是一個有趣的例子，而涉及其中的人可能根本從沒以這種用語來思考。畢竟，就如我們從圖10.1的Google Ngram圖表中可見，當中國第一次遇上蒸汽引擎時，這些用語在中文裡甚至不曾存在，而國內那些心靈手巧的思想和工匠，開始意識到正處於危急關頭中，於是開始急起直追。當時關於知識的事情就只分為六藝，所以在一開始時，這些來自西方世界的新概念，需要首先套入這舊有的框架，以作辨識。

在另一個Ngram圖表中可以看到其操作，先看看甚麼術語曾用來填補傳統詞彙的空隙，有三個普遍術語曾經被廣泛地用以處理這些外來新知識：「博物」——自然科學，但最初的概念已跨越了規範知識的框架；「格致」——探索事物或者鑽研其隱含的原理，清末時被挪用以指涉西方科學；「科學」——科學、科學知識，是當中最主要（起碼在Ngram圖表中所顯示）亦是最後一個（圖10.2）。將科學與被稱為「數學」的新思考方式（而非儒家的「數」的概念）作對照就會看到，在第一次鴉片戰爭前到第二次鴉片戰爭結束後幾年，以至通商口岸極速擴展的時期，這兩個新術語是如何被發揚光大。這尤其可見於後來蓬勃的海事工程——1860年代上海有9間由西方擁有和營運的造船廠，香港則有3間，廣州黃埔有4間，海事工程便是來自於它們的成果。而10年之內，由華商和外商共同持有的，則遍佈於廈門、福州、芝罘（煙台）以及其他地區。

最後，讓我們來看看中國如何接收「蒸汽」這概念。經過長時期轉化，西方人終能理解蒸汽為所有氣體的其中一種，但這個認知在中國則被轉化成兩個古老的概念：一個是「氣」——生命活動的原動力，另一個是「蒸」——一個日常煮食方法；這兩者又揉合成一個讓中國接受蒸汽動能的新概念——「蒸汽」（圖10.3）。他們必須以新觀念

理解蒸汽引擎如何操作，而不是如丁拱辰及其他人等，依賴傳統的「五行」邏輯。因為在中國傳統宇宙觀裡，水火互不相容，意味著任何試圖把它們合併的方式（就如蒸汽引擎般）都不被視為可行。另一種了解此觀點的方式就是把高壓蒸汽機中的蒸汽視為一種乾氣體，與此同烹飪食物的濕蒸汽作區分。如果人們使用的是五行學說，即「蒸汽」，便無法推導出蒸汽作為乾氣體的概念。

1861年，當時兩江（即今日江西、安徽、江蘇三省）總督、一等毅勇侯曾國藩，委託徐壽和華蘅芳建造一艘蒸汽船（圖10.4）。當然，他們二人對於如何實踐都沒有實際想法：為何他們要這樣做？眾所周知，徐壽自從1855年起，就對西方新機械工程感興趣，那時他才43歲。比徐壽年輕15歲的華蘅芳亦然，更專攻數理。瓦特有的是約早一世紀前的優勢，即實驗科學的傳統、西方傳統技術繪圖手法、早期的機床和精密工程等等，可是在曾國藩於1861年委託二人之前，這些似乎都不是他們能夠駕馭和獲得的技術。同樣，在此之前，他們因為興趣而確切地把工程學實踐到甚麼程度，也是不得而知。

但據知，徐和華似乎都下過功夫，鑽研多冊由倫敦傳道會的偉烈亞力（Alexander Wylie）編著，並由李善蘭翻譯、上海墨海書館出版的當代西方科學簡介。關於蒸汽引擎的一冊則是來自英國傳教師合信（Dr Benjamin Hobson）編著並於1849年出版的，特別是1851年的《博物新編》有一個章節闡釋了蒸汽引擎的原理和機制，包括固定式引擎及其零件的一些基本示意圖（圖10.5）。

徐壽和華蘅芳都是非常聰明，且曾在中國傳統體系裡接受過良好教育的人，就如其他充分受教育又進取的聰明人一樣，他們都很清楚自己應該做甚麼。儘管他們花了差不多一年時間。明顯地，除了合信（Hobson）的著作他們一定得到更多相關資料，他們曾經在其工作地點附近，參觀過於揚子江（長江）上的外國汽船。有趣的是，

他們跟從傳統的中國式途徑，首先製造出比例模型。1862年，那附有43毫米直徑氣缸的細小型號引擎以每分鐘240轉速度發出令人欣喜的聲音——雖然我們並未知道它是如何產生蒸汽的。

然而，製造模型和建造一個實際大小（即使是較小的）的蒸汽引擎有很大分別。造模型的話，使用傳統工藝的工具便足夠了。建造實際大小的蒸汽引擎所需要的更多——多很多。的而且確，這消耗了3年多、失敗過至少一次——由於二人還未完全弄清鍋爐的操作，因此那艘小船航行了約半公里便耗盡了蒸汽，然後才得以於1865年成功測試了只有8米長、依然很細小的明輪船。

若要達成他們想做的事，徐壽和華蘅芳可能需要西方的機床，和類似於繪圖工作室的工具。據知他們進口了一些零件，並很可能會利用所進口的西方機床，和1864年李鴻章的助手馬格里(Samuel Halliday Macartney)趁「阿思本艦隊」(Lay-Osborn flotilla)回英國前從其船隊買回來的工場設施。²⁶

能參考合信的书固然好，可是如圖10.4所顯示，若要製作出徐和華的產品，這樣的繪圖是嚴重地不足夠的。有關黃鵠號的故事我們所知不多，僅能窺見徐和華是如何成就這船的建造。畢竟，製造裝有銅水管、氣缸、活塞、連桿和軸頭、引擎的曲軸，以及所有較小零件（如螺帽、螺柱和閥門等）的鍋爐，需要圖紙、精密測量儀器和鑄造技能、車床、鑽頭等等，而非只是傳統中國木匠和金屬工匠的工具和測量設備。

而無論細節為何，黃鵠號成功下水和啟航，便讓中國踏出第一步，將西方世界300年龐大的S.T.E.A.M.融合發展，壓縮為數十年。結果就是到19世紀末，中國或多或少地已經趕上了，並加入了世界正在經歷的蒸汽革命。

從必須集科學家(scientists)、技術人員(technologists)、工程師(engineers)、藝術家(artists)和數學家

(mathematicians)於一身的徐壽和華蘅芳身上，我們正能夠看到S.T.E.A.M.五者並不能完全分割。它們是一個互動的整體，亦是一段由無數個舞者不斷旋轉、退後、挪前、側身、時而停頓、時而翻轉、永不止息的複雜群舞。徐壽明顯深明此理，並知道現代中國需要它，正因如此他在當時的英國駐上海領事麥都思(Walter Medhurst)的協助下，於1874年在上海外國租界創辦了格致書院。²⁷

26 有趣的是，首批成為中國公務員的外國人之一的馬格里爵士，是以1793年出訪中國失敗聞名的英國特使馬夏爾尼勳爵(Lord Macartney)的親戚。

27 今日的上海市格致中學。

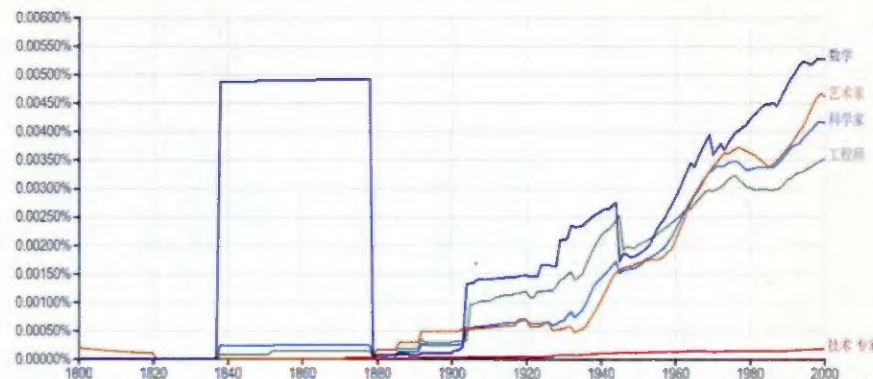


Figure 10.1: The incidence of S.T.E.A.M. in published Chinese books, 1800–2000.²⁸
(Source: Google Ngram.)

圖10.1：「S.T.E.A.M.」中多個概念在1800至2000年出版的華文書籍中的出現率。²⁸
(資料來源：Google Ngram。)

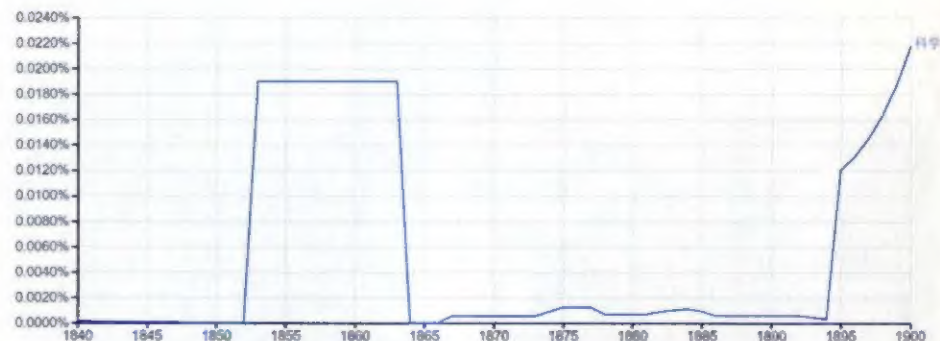


Figure 10.2: The arrival of *kexue* (科學) in Chinese written work 1840 to 1900.
(Source: Google Ngram.)

圖10.2：「科學」這一詞於1840至1900年始出現在華文書寫中。
(資料來源：Google Ngram。)

28 This is a necessarily imperfect guide because the number of Chinese titles as yet in the Google database is small compared to works in European languages, and smaller still compared to works in English. In addition, some common modern Chinese terms, such as the characters for technologist and mathematician, are not acceptable to the Ngram algorithm. The graph has been kept because it is indicative and nothing more.

28 這當然是不完美的指引，因為對比於歐洲語言，中文書籍在Google資料庫中的數量很少，與英語作品相比就更少。而且，一些普遍的現代華文詞彙，例如某些工藝或數理的字元並不被Ngram的演算法所接納。保留此圖表只因它的指示性，僅此而已。



Figure 10.3: The arrival of 'steam' in China.
(Source: Google Ngram.)

圖 10.3：「蒸汽」傳到中國。
(資料來源：Google Ngram。)



Figure 10.4: Xu Zhou and Hua Hengfang.
(Source: Chinese Wikipedia for Xu Zhou and <https://baike.baidu.com/item/%E5%8D%8E%E8%98%85%E8%8A%B3> for Hua Hengfang.)

圖 10.4：徐壽與華蘅芳。
(資料來源：維基百科及百度百科。)

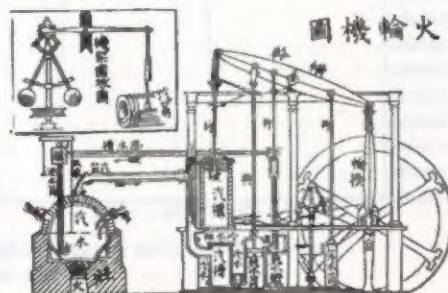


Figure 10.5: Illustration of a steam engine
(a very old-fashioned 18th century one with a kettle boiler and no valves and valve mechanism!)
in Hobson's *Bowu xinbian* (博物新編).

圖 10.5：合信《博物新編》中蒸汽引擎的插圖
(一個非常舊式的 18 世紀款，附帶水煲式鍋爐，
且沒有閥門和閥動機關！)。

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